2021 HOUSE ENERGY AND NATURAL RESOURCES

HB 1401

2021 HOUSE STANDING COMMITTEE MINUTES

Energy and Natural Resources Committee
Coteau AB Room, State Capitol

HB 1401 AM
1/28/2021

Relating to monitoring and regulation of special waste in ground water and to provide a penalty

9:00 AM

Present: Representatives Porter, Damschen, Anderson, Bosch, Devlin, Heinert, Keiser, Lefor, Marschall, Roers Jones, Guggisburg, M Ruby, Zubke, and Ista.

Discussion Topics:
- Brown zones, dead farmland, underground water
- Waste pits and contamination
- Ground water protection
- Canadian remedy
- Monitoring update
- Fiscal note
- Legacy wells jurisdiction
- Oil and Gas Division
- Water sampling and testing

#3990, #3991, #3992, #3993, #3994 Rep M Nelson
#3970 Troy Coons, chairman NW Landowners Association
#3888 Chuck Hyatt, director- Division of Waste Mgmt- Dept of Environmental Quality

Additional written testimony:
#3996, #4656

10:05 AM

Leaving the hearing open and Lynn Helms will come down and speak to the committee.

Kathleen Davis, Committee Clerk

Testimony for HB1401

Representative Marvin E. Nelson, District 9

House Energy and Natural Resources Committee

Representative Todd Porter, Chairman.

HB1401 is to have the Environmental Division develop monitoring of special waste. That's what oilfield waste is called because by law it isn't hazardous waste. Develop standards for ground water and special waste, and if found, to develop plans about what to do to prevent contamination.

Emphasis would be on the legacy of the saltwater leaching pits used not so many years ago. For a long time they were unlined. Then there was a period where liners were required, but when they were no longer going to be used, many had what is called spidering done. That is taking a backhoe and digging trenches out from the pit to quickly leach the waste into the surrounding land. Much like a septic drainfield.

There they sit. Creating a brown zone of dead farmland. Clearly they are contaminating the shallow diffuse water but what are they doing to deeper water What are they doing to drinking water, to stock water, and to wetlands? We really don't know.

So the first part of any problem is finding out if there is a problem, then measuring the problem and then we could proceed with mitigation or cleanup.

Traditional ways of delineation are slow, expensive and very limited in scope.

I would say that I think it can be done quickest and most accurately if we start with electromagnetic machines that show salts through their high conductivity.

The USGS has done some of this using helicopter flown EM machines. They've used a frequency domain machine that can read to about 200 feet. The Sheridan County, Montana USGS study was done partly that way. They originally used it to trace contamination of home water wells that came from a long ways away. Movement of a half mile is pretty common.

There is also the EM31 for ground that does a one dimensional image for 20 feet or so depending on conductivity. After that an ohmmapper could be used to provide a three dimensional image of the contamination to approximately 30 foot depth.

Where contamination goes still deeper time domain machines can go to hundreds if not thousands of feet. The technology is much quicker and lower cost than drilling wells and testing water.

The online testimony has a copy of a presentation by Ed Murphy, state geologist about the various studies that have been done. For those of you who haven't already seen it, it's a very good self-explanatory presentation.

There is also a USGS study of about 30 wetlands where they predict how long under natural conditions it would take them to return to pre oil conditions. Acute toxicity from 2045 to 2113, chronic from 2069 to 2160 and background from 2126 to 2275. That assuming no continuing contamination and that surface wetlands that occasionally flush.

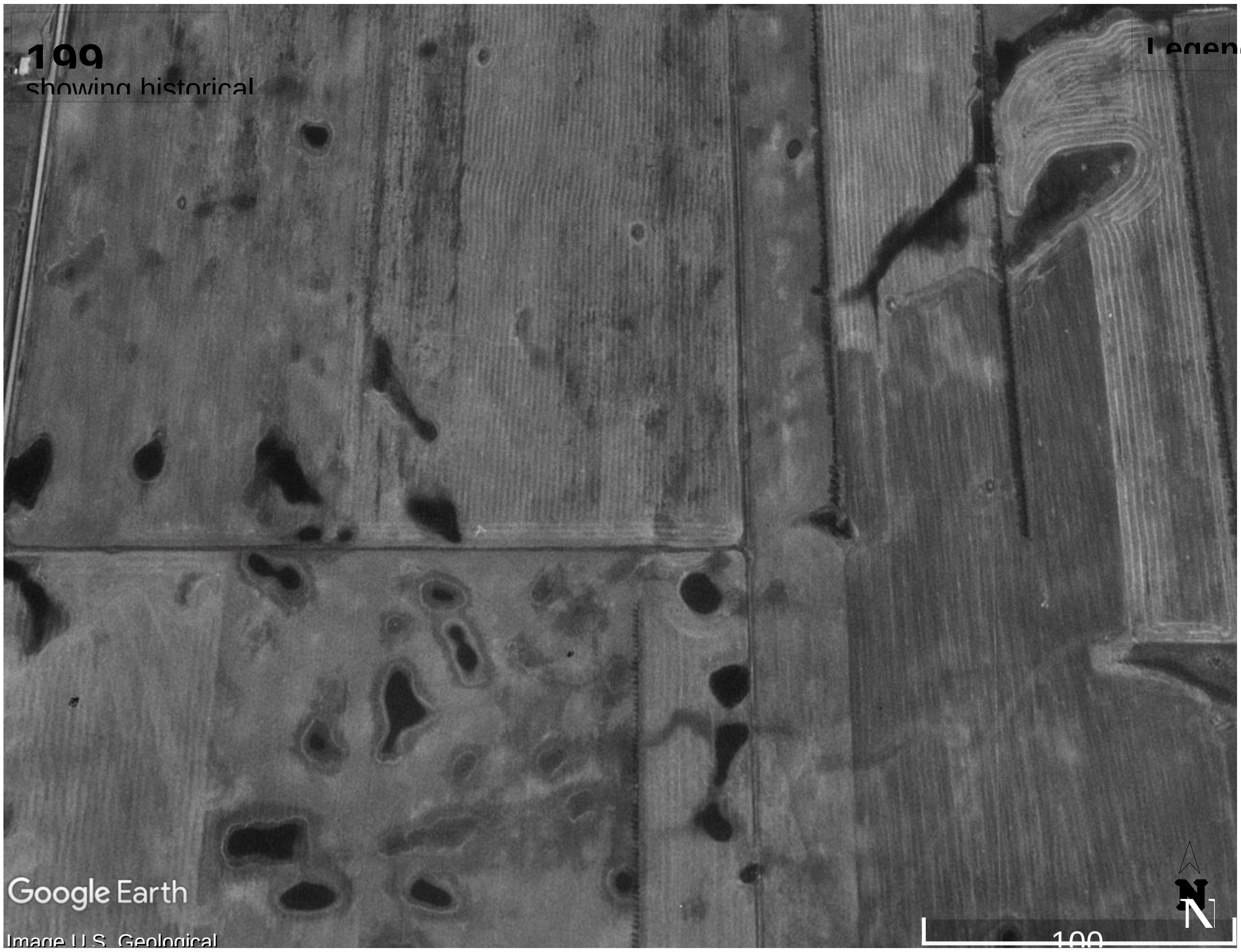
Now let's take a look from above

1997 Murphy

2 pits, notice trees

2016 Murphy

Trees gone, saline area greatly expanded. Can see gathering pipeline locations.



1995 Renville

Before oil development. After pits were used.

2021 Renville

Salts showing, pipelines. Problems aren't limited to pits.

Science of the Total Environment 690 (2019) 522–533

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Predicting attenuation of salinized surface- and groundwater-resources from legacy energy development in the Prairie Pothole Region

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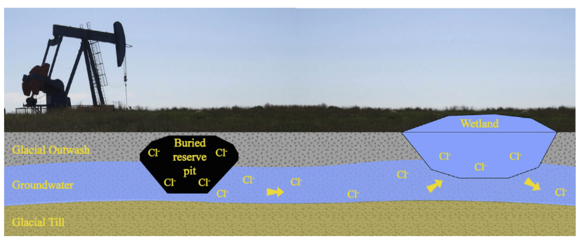
HIGHLIGHTS

- The Prairie Pothole Region overlies part of the oil and gas producing Williston Basin.
- Persistent salinization of aquatic resources occurred from legacy energy development.
- Natural attenuation of chloride to background levels will take another 150–250 years.
- Chloride emitted in 2018 will migrate nearly 1 km until dilution to background levels.
- One third of Prairie Pothole Region wetlands are within 1 km of energy development.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 2 April 2019
Received in revised form 14 June 2019
Accepted 25 June 2019
Available online 26 June 2019

Editor: José Virgílio Cruz

Keywords:
Wastewater
Brine
Wetlands
Williston Basin
Amphibian

ABSTRACT

Oil and gas (energy) development in the Williston Basin, which partly underlies the Prairie Pothole Region in central North America, has helped meet U.S. energy demand for decades. Historical handling and disposal practices of saline wastewater co-produced during energy development resulted in salinization of surface and groundwater at numerous legacy energy sites. Thirty years of monitoring (1988–2018) at Goose Lake, which has been producing since the 1960s, documents long-term spatial and temporal changes in water quality from legacy energy development. Surface water quality was highly variable and decoupled from changes in groundwater quality, likely due to annual and regional climatic fluctuations. Therefore, changes in surface water-quality were not considered a reliable indicator of subsurface chloride migration. However, chloride concentrations in monitoring wells near wastewater sources exhibited systematic temporal reductions allowing for estimates of the time required for natural attenuation of groundwater to U.S. Environmental Protection Agency acute and chronic chloride toxicity benchmarks and a local background level. Point attenuation rates differed based on sediment type (outwash vs till) and yielded a range of predicted years when water-quality targets will be reached: acute – 2045 to 2113; chronic – 2069 to 2160; background – 2126 to 2275. Bulk attenuation rates from four separate years of data were used to calculate the distances chloride could migrate downgradient from the largest wastewater source. Potential distances of downgradient migration before dilution to water-quality targets decreased

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https://doi.org/10.1016/j.scitotenv.2019.06.428

from 1989 to 2018: acute – 949 to 673 m; chronic – 1220 to 922 m; background – 1878 to 1525 m. Several downgradient wetlands are within these distances and will continue to receive saline contaminated groundwater for years. While these results demonstrate chloride attenuation at a legacy energy site, they also highlight the persistence of saline wastewater contamination and the need to mitigate future spills to prevent long-term salinization from energy development.

1. Introduction

Saline water (often referred to as brine) is commonly co-produced with oil and gas (energy) resources and the release of oilfield wastewaters results in the secondary salinization of soils (Keiffer and Ungar, 2002; Pichtel, 2016), surface water (Brantley et al., 2014; Cozzarelli et al., 2017; Vengosh et al., 2014), and groundwater (Fontenot et al., 2013; Jackson et al., 2013; Preston et al., 2014). In addition to salts, oilfield wastewaters include toxic and radioactive elements from the producing formation and chemical additives used during drilling and production (Engle et al., 2014; Lauer et al., 2016). The rapid increase in domestic U.S. energy production from unconventional resources has been accompanied by a concurrent increase in the volume of produced water, with the U.S. generating over 21 billion barrels of wastewater annually (Veil, 2015). Environmental effects of produced water spills have been studied at numerous energy plays (e.g., Bakken Formation, North Dakota (Cozzarelli et al., 2017); Barnett Formation, Texas (Fontenot et al., 2013); Marcellus Formation, Pennsylvania (Jackson et al., 2013)); however, differences in wastewater chemistry, contaminant pathways, climate, and physiography exert considerable influence on the fate and transport of oilfield wastewaters and the associated risks to natural resources and local organisms (Cozzarelli et al., 2017). Therefore, understanding the long-term effects of secondary salinization from legacy energy production within an individual energy play is critical to developing effective remediation strategies for current and future discharges of oil and gas wastewaters.

The Williston Basin has been a leading source of U.S. energy production since the 1960s. Overlying the northeastern portion of the Williston Basin is the Prairie Pothole Region (PPR), a glacial till plain characterized by numerous depressional wetlands within a grassland matrix that provides critical habitat to migratory waterfowl (Batt et al., 1989), grassland birds (Swengel and Swengel, 1998), aquatic and terrestrial invertebrates (Euliss et al., 1999), amphibians (Mushet et al., 2012), and other wetland-dependent wildlife. Secondary salinization from legacy and contemporary energy production is well documented within the PPR (Cozzarelli et al., 2017; Lauer et al., 2016; Preston et al., 2014; Thamke and Smith, 2014; Reiten and Tischmak, 1993; Rouse et al., 2013) and has resulted in persistent increases in surface and groundwater salinity (Beal et al., 1987; Preston et al., 2014; Rouse et al., 2013), decreased biodiversity and ecosystem services in PPR wetlands (Hossack et al., 2018, 2017; Preston et al., 2018; Preston and Ray, 2017; Smalling et al., 2019), and reduced seed germination of pasture and agricultural crops (Keiffer and Ungar, 2002; Meehan et al., 2017; Munn and Stewart, 1989).

A major source of saline contamination in the Williston Basin is from legacy practices that used unlined earthen reserve or evaporation pits to store and dispose of co-produced water (Beal et al., 1987; Lauer et al., 2016; Murphy et al., 1988; Preston et al., 2014; Reiten and Tischmak, 1993). Reserve pits were used temporarily (months to years) at individual production well sites until more permanent infrastructure was constructed. Evaporation pits were generally located at collection facilities, serviced multiple production wells, and operated for extended periods (years to decades) to dispose of wastewater through evaporation and infiltration. Pits were reclaimed by burial after use, and it is estimated that the average reserve pit held approximately 260 tons of dissolved sodium chloride salts during operation (Reiten and Tischmak, 1993). Of particular concern are numerous legacy pits constructed in permeable glacial outwash deposits, which allowed for rapid infiltration of salts and other contaminants into the shallow groundwater system. The high hydraulic conductivity of these deposits promoted the development of laterally extensive groundwater plumes that could discharge into downgradient wetlands (Baker and Brendecke, 1983; Beal et al., 1987; Preston and Chesley-Preston, 2015; Preston et al., 2014; Reiten and Tischmak, 1993; Rouse et al., 2013). More than 20,500 oil and gas wells were drilled in the Williston Basin prior to pit regulations in the 1980s and 1990s (Beal et al., 1987; Preston et al., 2014). These abandoned pits represent potential point source locations of saline wastewater. Pipeline breaks, spills, illegal discharges, and reuse applications, such as road deicers, are also contemporary sources of saline contamination.

Much of the surface and shallow groundwater in the PPR has naturally elevated total dissolved solid (TDS) concentrations; however, the chemistry of these naturally saline waters is distinctly different from the deep formational groundwater in the production zones (oilfield wastewater). The salinity of surface waters in the PPR generally increases along the continuum of groundwater recharge, flow-through, and discharge wetlands (LaBaugh et al., 1987; Winter, 2003), yet TDS concentrations are generally <10,000 mg/L (Tangen et al., 2014). TDS concentrations in the shallow aquifers are generally below 3000 mg/L (Gorham et al., 1983). Wetlands unaffected by oilfield wastewaters in the PPR are predominantly sulfate (62% of wetlands) or magnesium (33%) type waters with relatively few wetlands containing water dominated by chloride (5%; Swanson et al., 1988). In contrast, deep formational waters in the Williston Basin are some of the most saline waters in the U.S. and have TDS concentrations ranging from 30,000 to >450,000 mg/L, and ionic compositions are typically dominated by chloride (Iampen and Rostron, 2000; Otton, 2006). The introduction of oilfield wastewaters to uncontaminated waters can increase TDS and specific conductance and shift sulfate/bicarbonate-dominated waters to chloride-dominated waters (Preston et al., 2014; Reiten and Tischmak, 1993).

Ecological manifestations of wastewater contamination in the PPR are numerous and span multiple trophic levels. Contamination from oilfield wastewaters reduced the above-ground biomass of hardstem bulrush (*Schoenoplectus acutus*) and taxonomic richness and diversity of macroinvertebrates in PPR wetlands (Preston et al., 2018; Preston and Ray, 2017). Boreal chorus frog (*Pseudacris maculata*) larvae reared from contaminated sediments had reduced survival rates relative to larvae reared from uncontaminated sediments (Hossack et al., 2017) and contaminated wetlands in the PPR had lower abundances of boreal chorus frogs, northern leopard frogs (*Rana* [= *Lithobates*] *pipiens*), and barred tiger salamanders (*Ambystoma mavortium*) compared to uncontaminated wetlands (Hossack et al., 2018). Finally, survival of larval fathead minnows (*Pimephales promelas*) was reduced in a North Dakota stream over a 6-month period after a wastewater spill (Cozzarelli et al., 2017). Combined, these studies imply that the effects of wastewater contamination may be synergistic responses to salt toxicity and other associated contaminants, such as metals and radionuclides, commonly found in oilfield wastewater (Farag and Harper, 2014).

The Williston Basin contains tens of thousands of oilfield sites with buried, unlined reserve pits and examining the processes of secondary salinization at a long-term monitoring site provides a better understanding of the likely fate and transport of contaminants at other legacy sites in the basin and provides critical knowledge to aid future wastewater management and restoration efforts. The Goose Lake study site, located in the PPR of the Williston Basin, has a well-documented history of secondary salinization from oil and gas development (Preston et al., 2014; Peterman et al., 2012; Reiten and Tischmak, 1993; Rouse et al., 2013). Historical data and recent water-quality sampling in 2015 and 2018 provide a 30-year time series to examine long-term spatial and temporal changes in surface- and groundwater-quality at a legacy energy development site. Previous studies identified contaminant sources and likely contamination pathways and began to explore changes in surface and groundwater-quality. Recently collected data allowed for enhanced understanding of the temporal (long-term and seasonal) changes in the geochemical signatures of wastewater-contaminated surface and groundwater resources. Specifically, our main objectives were to evaluate the influences of regional climatic fluctuations on the observed relations between surface and groundwater salinity and to provide the first known quantitative predictions on the timeframe required for natural attenuation of chloride in shallow groundwater systems adjacent to known wastewater sources in the Williston Basin.

2. Methods

2.1. Site description

The Goose Lake study site (Goose Lake hereafter) in Sheridan County, northeast Montana, USA, includes the Rabenberg Waterfowl Production Area and surrounding private lands (Fig. 1; Reiten and Tischmak, 1993). Potential wastewater sources to aquatic resources at Goose Lake include reserve pits at 11 oilfield sites, targeting the Mississippian-aged Madison Limestone, installed during 1965–1969 and an evaporation pit at the tank battery. Based on historical aerial photos, the individual reserve pits were generally active for a few years after well construction, whereas the evaporation pit at the tank battery was in operation from at least 1967 through 1992. Other potential wastewater sources include spills and intentional discharges onto the land surface and into nearby wetlands as reported by local

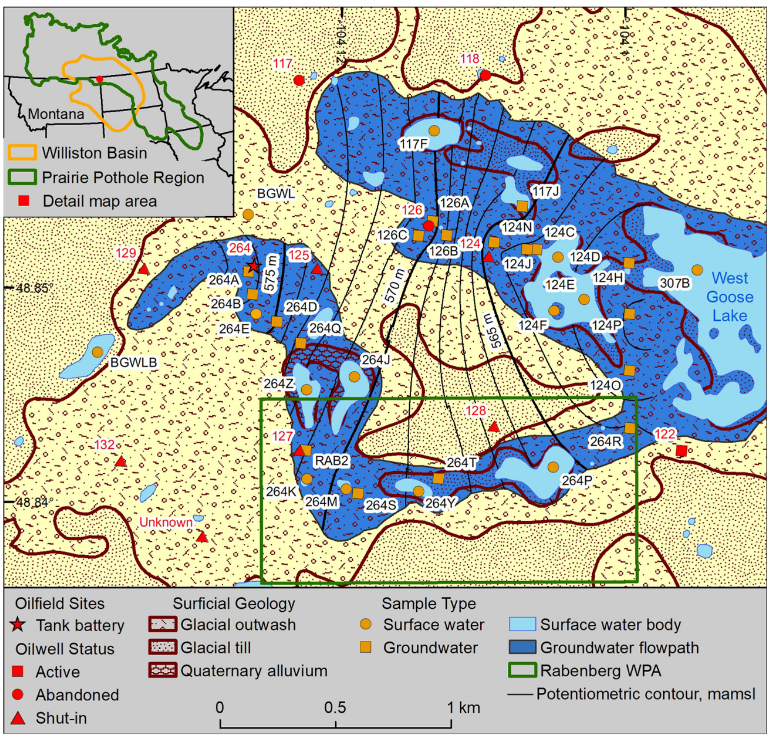

Fig. 1. Map of the Goose Lake study site (Sheridan County, Montana, USA) showing locations of the Rabenberg Waterfowl Production area (WPA), oilfield infrastructure, surface (wetland) and groundwater samples, surficial geology (Reiten and Tischmak, 1993), the northern and southern flowpaths and the associated potentiometric contours (altitude at which water level would have stood in tightly cased wells, May, 2009. Contour interval 1 m, Datum is mamsl – meters above mean sea level). Numbers next to oilfield infrastructure and water quality sampling locations refer to site names in the text. Surface water sites BGWL and BGWL-B are hydraulically upgradient of oilfield sites and are uncontaminated by oilfield wastewaters whereas the remainder of the water-quality sites are downgradient of oilfield sites and have wastewater contamination signatures. Inset map shows the location of the study site in relation to the Williston Basin and Prairie Pothole Region.

landowners and previous researchers (Reiten and Tischmak, 1993). As of 1 April 2019, four of the 11 oil wells were plugged and abandoned, six were shut-in (meaning they could produce again), and one was active, as was the tank battery. Oilfield site names follow the nomenclature of Reiten and Tischmak (1993).

Goose Lake is located within the Missouri Coteau, an area characterized by hummocky terrain with poorly developed drainage systems and thousands of depressional wetlands (Martin and Hartman, 1987). Surficial geology of the Missouri Coteau is comprised of tens of meters of glacial deposits consisting primarily of fine-grained, clay-rich glacial tills and coarse-grained glaciofluvial (e.g., outwash) deposits (Fullerton et al., 2004). Goose Lake sits at a transition from clay-rich glacial till in the northwest portion of the study area to coarse-grained outwash deposits overlying glacial till in the southeast part of the study area (Fig. 1). The outwash deposits are 1–7 m thick and saturated, creating unconfined aquifer conditions, and these deposits have allowed contamination to spread across the study site (Preston et al., 2014; Reiten and Tischmak, 1993; Rouse et al., 2013). Two groundwater flowpaths have been delineated in the outwash deposits, with both flowpaths discharging into West Goose Lake (site 307B; Reiten and Tischmak, 1993). Depth to groundwater generally becomes shallower downgradient in the northern flowpath, whereas the opposite is true for the southern flowpath. As of 2009, wastewater plumes had migrated 600–1600 m from probable sources and contaminated both flowpaths as well as all wetlands downgradient from the oilfield sites (Preston et al., 2014; Reiten and Tischmak, 1993; Rouse et al., 2013). Wetlands 124D, 124E, and 124F, which appear as a single water body in the National Wetland Inventory dataset (Fig. 1; U.S. Fish and Wildlife Service (USFWS, 2015), are three distinct wetland basins most years.

To place the timing of energy development and sample collection into a historical climate perspective, precipitation data were obtained from nearby U.S. Cooperative Observer Program (National Oceanic and Atmospheric Administration (NOAA, 2018) stations for January 1960 – September 2018 (Fig. 2). When available, data from Westby, Montana (station ID 248777; 674 months), located 5 km northeast of Goose Lake, were used. Missing data were filled in first from Fortuna, North Dakota (323196; 23) and then from Plentywood, Montana (246586; 5), which are located 25 km northeast and 34 km southwest of Goose Lake, respectively. No data were available from either station for March 2011. Goose Lake has a semi-arid climate characterized by warm summers and cold winters (average July and January temperatures in Westby, Montana of 20.4° and −14.2 °C, respectively). Average precipitation in Westby, Montana, is 35.8 cm/year with over one-half (18 cm) falling in June, July, and August, primarily during thunderstorms. These storms are often localized and can produce considerable variation in precipitation totals over tens of kilometers. Additionally, total precipitation generally increases from west to east across the Williston Basin. Energy development in the late-1960s occurred during a relatively wet period that continued until approximately 1980. Between 1980 and 1990, precipitation was generally below average, followed by above-average precipitation between 1990 and 2000. Drier conditions returned from 2000 to 2009, with variable conditions from 2010 to 2018 including the wettest (2011) year since 1960.

2.2. Temporal changes in water-quality

2.2.1. Previous research

Goose Lake has a long history of water-quality monitoring, and a combination of previously published and new data were used to extend estimates of the fate and transport of chloride. For brevity, sampling procedures and analytical methods of historical data are provided in the referenced literature. The Montana Bureau of Mines and Geology (MBMG) conducted the initial research at Goose Lake, installing the majority of shallow monitoring wells and collecting numerous groundwater and surface-water samples from 1988 to 1990. All sites shown in Fig. 1 were sampled by MBMG except for BGWL, BGWL-B, RAB2, and 264Y (Reiten and Tischmak, 1993). The U.S. Fish and Wildlife Service resampled seven locations (264A, 264B, 264D, 264J, 264K, 264M, and 264P) and installed a new groundwater well (RAB2) in 2005 and resampled eight locations (117F, 124C, 124H, 124J, 124N, 124O, 124P, and 126B) in 2006 (Rouse et al., 2013). In 2009, the U.S. Geological Survey (USGS) sampled all sites except for BGWL-B, 264B and 264Z and also collected a produced water sample from the tank battery to characterize contaminant sources at Goose Lake (Preston et al., 2014; Preston et al., 2012). Water samples were analyzed for major ions and trace-metals during all sampling efforts.

2.2.2. New sample collection and comparison metrics

The USGS conducted additional, targeted water-quality sampling in 2015 followed by sampling four wetlands and all but one groundwater well in 2018 using published methods (USGS, variously dated). Water-quality samples were collected from three wetlands (BGWL-B, 264J, and 264P), three groundwater wells (264D, 264T, 264R), and from the inflow and separator tank at the tank battery (264) in 2015. Samples were analyzed for major ion and trace-metal concentrations at the Reston Biogeochemical Processes in Groundwater Laboratory (Reston, Virginia, USA) using published methods (USEPA, 2007; Cozzarelli et al., 2017). Chloride concentration and specific conductance were measured onsite at five additional wetlands (124F, 264E, 264K, and 264M) during July 2015. Chloride concentrations were determined onsite with Hach QuanTab test strips (catalog nos. 27449-40, 27513-40) and specific conductance was measured with a YSI EXO multimeter. Onsite chloride and specific conductance measurements were collected from wetlands 264J, 264K, and 264M in May 2018 and 307B in June 2018 using Hach

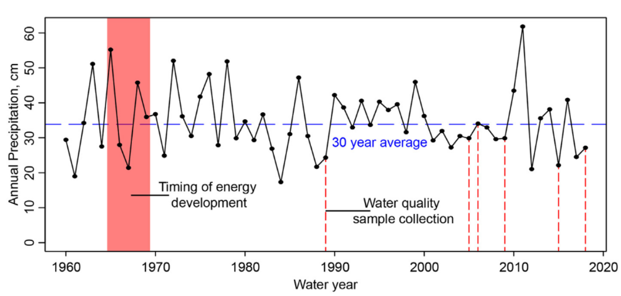

Fig. 2. Total precipitation per water year (October 1–September 30) at Westby, Montana, which is located approximately 5 km northeast of the Goose Lake study site, Sheridan County, Montana, USA. Data from NOAA (2018) with the 30-year average calculated from 1988 to 2018.

chloride test strips and a Hana HI98130 meter. Both Hossack et al. (2018) and Reiten and Tischmak (1993) reported a nearly 1:1 relations between laboratory- and QuanTab-derived chloride concentrations across a range of values and data from both methods are used interchangeably here. Two groundwater wells (124N and 264D) were sampled in May 2018 and all groundwater wells (except 124H) were sampled during September 2018. The 2018 groundwater samples were field filtered and shipped on ice for analysis at the MBMG Analytical Laboratory (Butte, Montana, USA) using published methods (U.S. Environmental Protection Agency (USEPA, 2007)); however, May samples were analyzed for chloride and specific conductance only, whereas September samples were analyzed for major ions and trace-metals. Chloride and specific conductance data collected from 1989-2018 at Goose Lake are provided in Preston (2019).

Given the high variability in natural salinity in the PPR, an empirically derived Contamination Index (CI) has been used at Goose Lake to differentiate naturally saline waters from those contaminated by oilfield wastewaters (Reiten and Tischmak, 1993). The CI is the ratio of chloride concertation (mg/L) to specific conductance (μS/cm) in a water sample. CI values >0.035 in the region have typically been considered indicative of wastewater contamination whereas CI values >0.35 and chloride concentrations >10,000 mg/L indicate extremely contaminated sites (Preston et al., 2014). In general, the changes in surface water chemistry are more dynamic than groundwater. Therefore, temporal changes in water quality between the different sampling efforts are evaluated by comparing changes in both CI values and accompanying chloride concentrations.

2.3. Natural attenuation rates

Natural attenuation rates for a given contaminant are often calculated from first-order relations developed from temporal concentration data from single monitoring wells and/or from concentration versus distance relations developed from numerous monitoring wells sampled concurrently (Beyer et al., 2007; Newell et al., 2002). Point attenuation rates from single monitoring wells allow for the estimation of the time required to reach remediation or water-quality targets at that location, whereas bulk attenuation rates provide distance-based estimates to evaluate whether a plume will expand, remain stable, or shrink. These approaches are best documented at petroleum spill sites where contaminants experience microbial degradation or sorption reactions; however, attenuation rates can also be calculated for conservative contaminants (such as chloride at Goose Lake) where the only form of attenuation is advective-dispersive transport from the source zone (Newell et al., 2002).

Chloride concentration point attenuation rates were calculated at six groundwater monitoring wells (124N, 126B, 264A, 264B, 264D, and 264Q; Fig. 1) near known wastewater source zones. Point attenuation rates for each monitoring well were calculated from the slope of a linear regression fit to log transformed chloride concentration data as a function of time (Table 1). The 2018 chloride concentrations from monitoring well 124N were highly elevated relative to 2009, possibly owing to the downgradient migration of wastewater from oilfield site 126, and point attenuation rates were calculated both with and without the 2018 data. Bulk attenuation rates were calculated from the slope of linear regressions fit to log transformed chloride concentration data from groundwater wells 264A, 264B, 264D, and 264Q, located on the inferred centerline of the contaminant plume (Fig. 1), as a function of distance from the tank battery (264). Individual bulk attenuation rates were obtained from log transformed chloride concentrations from the 1989, 2005, 2009, and 2018 data to evaluate potential temporal changes in bulk attenuation rates (Table 1). Robust standard errors were calculated for all regression models. Statistical differences in regression coefficients (rate constants) were determined with Tukey pairwise comparisons for both the point attenuation and bulk attenuation constants. From the point attenuation constants, the time required for chloride concentrations to reach three water-quality targets were predicted for each well: acute (860 mg/L) and chronic (230 mg/L) toxicity benchmarks (USEPA, 1988) and a local background level (9.5 mg/L; the average chloride concentration of uncontaminated groundwater samples from 126C and 264T in 1989) were predicted for each well. From the bulk attenuation constants, the distance that chloride emitted from the source zone at the time of sampling would travel before being diluted to these same water-quality targets was calculated.

3. Results

3.1. Temporal changes in water-quality

The 2015 produced-water and separator-tank samples (oilfield wastewaters) generally had greater major-ion concentrations than the 2009 produced-water sample; however, the relative trends in major-ion distributions were similar. For example, specific conductance and chloride concentrations in produced water samples were 229,000 μS/cm and 145,430 mg/L in 2015 compared to 223,000 μS/cm and 121,000 mg/L in 2009. Produced-water samples in both years were dominated by sodium and chloride ions and contained elevated concentrations of other major ions including calcium, magnesium, potassium, and ammonium and elements such as barium, bromine, lithium, nickel, rubidium, and strontium relative to uncontaminated surface and groundwater (Preston et al., 2014; Hossack et al., 2017; Smalling et al., 2019).

Results for water-quality samples collected during 1989, 2005–06, and 2009 are provided in Table 1 of Preston et al. (2012) and briefly summarized here. Initial sampling in 1989 revealed widespread chloride contamination at Goose Lake; however, groundwater from two monitoring wells (126C and 264T) had CI values less than contamination threshold (0.035; Figs. 3 and 4). Samples from 3 wetlands and 10

Table 1
Sample dates and chloride concentrations (mg/L) from groundwater samples used to determine natural attenuation rates at the Goose Lake study site in Sheridan County, Montana.

124N		126B		264A		264B		264D		264Q	
Date	Chloride	Date	Chloride	Date	Chloride	Date	Chloride	Date	Chloride	Date	Chloride
		12/13/1988[a]	24,630	12/12/1988[a]	72,400	12/12/1988[a]	50,200	12/13/1988[a]	21,760	10/13/1989	10,300
10/17/1989[b]	12,000	4/20/1989[b]	26,540	10/13/1989[b]	73,395	4/20/1989[b]	37,780	4/20/1989[b]	18,120	6/26/1990[a]	10,465
6/20/1990[a]	10,915	6/20/1990[a]	26,705	6/27/1990[a]	54,600	6/26/1990[a]	48,740	6/27/1990[a]	18,150		
				9/15/2005[c]	30,841	9/15/2005[c]	22,638	9/15/2005[c]	7302	9/15/2005[c]	11,330
4/4/2006[c]	4217	4/5/2006[c]	15,382								
5/14/2009[c]	3340	5/14/2009[c]	15,800	5/13/2009[c]	37,500			5/15/2009[c]	5330	5/15/2009[c]	3940
								6/23/2015[c]	4644		
5/20/2018[c]	3860							5/20/2018[c]	3743		
9/4/2018[c]	5221	9/5/2018[c]	11,458	9/5/2018[c]	21,972	9/5/2018[c]	17,298	9/5/2018[c]	4248	9/6/2018[c]	3356

[a] Onsite chloride measurement.
[b] Average of concurrent onsite and laboratory measurements.
[c] Laboratory measurement.

groundwater wells classified as extremely contaminated (CI > 0.35 and chloride concentration >10,000 mg/L) in 1989. All water-quality samples in 2005–06, which did not include reference sites BGWL and BGWL-B or groundwater wells 126C and 264 T, indicated wastewater contamination. Between 1989 and 2005–06, chloride concentrations had increased in three wetland (range: 860 to 1800%) and two groundwater samples (range: 23 to 34%) and decreased in one wetland (18%) and nine groundwater samples (range: 31 to 84%). Samples from five groundwater wells were classified as extremely contaminated in 2005–06. In 2009, all sampled sites except the background wetland (BGWL), which is upgradient from oilfield sites, were contaminated by wastewater, including the two groundwater wells that had not been contaminated in 1989. Between 2005 and 06 and 2009, chloride concentrations had decreased in all four wetlands (range: 53 to 92%) and four groundwater wells (range: 21 to 78%) and increased in six groundwater wells (range: 3 to 570%). Samples from four groundwater wells were classified as extremely contaminated in 2009.

New water-quality sampling in 2015 and 2018 indicated persistent wastewater contamination at Goose Lake (Figs. 3 and 4); however, chloride concentrations generally decreased in groundwater samples and increased in surface water samples relative to previous sampling events. A second background wetland (BGWL-B) upgradient from oilfield sites was first sampled in 2015, and along with the 2009 BGWL sample, represents surface water from wetlands unaffected by wastewater. Surface-water samples from these wetlands had the lowest chloride concentrations (10 and 9 mg/L, respectively) at Goose Lake. Between 2009 and 2015, chloride concentrations had decreased in two groundwater samples (6 and 13%) and increased in one groundwater sample (120%) and in all six contaminated wetland samples (range 0.2 to 3800%). No water samples collected in 2015 were classified as extremely contaminated. Wastewater contamination was evident in all 2018 water-quality samples. Between 2015 and 2018, chloride concentrations had decreased in two of the three groundwater (9 and 25%) and wetland samples (5 and 80%) and increased in the other groundwater (22%) and wetland sample (270%). The other 15 sites sampled in 2018 had not been sampled since 2009 and chloride concentrations decreased since that time in 10 groundwater samples (range 15 to 50%) and increased in samples from the other 4 groundwater wells (range 63 to 390%) and wetland 307B (120%). Samples from two groundwater wells were classified as extremely contaminated in 2018. In general, the groundwater samples in 2015 and 2018 that had decreased chloride concentrations relative to 2009 were from wells located near known wastewater source zones whereas samples with increased chloride concentrations were from wells located in distal portions of the flowpaths.

3.2. Natural attenuation rates

Chloride concentrations in six groundwater wells (124N, 126B, 264A, 264B, 264D, and 264Q) near wastewater source zones decreased between 1989 and 2018, with these significant decreases modeled by a first-order decay constant ($p < 0.05$ for all regressions) allowing for determination of point attenuation rates for each groundwater well (Fig. 5, Table 2). There were statistical differences ($p < 0.05$ in Tukey pairwise comparisons) in point attenuation rate constants between different wells. The rates for wells 124N (excluding the 2018 data) and 264D were greater than 126B, 264A and 264B whereas the rate constant for 264Q was not significantly different from any other rate constant. There is a considerable range in the time required to reach the three water-quality targets based on the regression equations for the different groundwater wells. Depending on the individual site, return to the EPA acute toxicity benchmark (860 mg/L) is not predicted until the years 2045 to 2113, EPA chronic toxicity (230 mg/L) is not predicted until 2069 to 2160, and local background (9.5 mg/L) is not predicted until 2126 to 2275. Although chloride concentrations in groundwater well 124N also followed a first-order decay constant ($p < 0.05$) both with and without 2018 data, the increased chloride concentration in 2018 limits the strength of the predictions to reach water-quality targets and were not calculated.

Chloride concentrations in 1989, 2005, 2009, and 2018 decreased with distance from the tank battery (264), with these significant decreases also modeled by a first-order decay constant ($p < 0.05$ for all regressions) allowing for determination of bulk attenuation rates for each year (Fig. 5, Table 3). There were minor differences in bulk attenuation rates between the different years; however, these differences were not statistically different ($p > 0.05$ in Tukey pairwise comparisons). Continued flushing of chloride from the source area has reduced the potential downgradient migration distance to achieve the three water-quality targets. In 1989, the respective distance that chloride was predicted to migrate downgradient before dilution to EPA acute, EPA chronic, and background levels were 949, 1220, and 1878 m whereas these predicted distances were reduced to 673, 922, 1525 m in 2018. Several wetlands in the southern flowpath are within these distances as measured downgradient from the tank battery; 264Z (500 m downgradient), 264 J (610 m), 264 K (1,000 m), 264 M (1030 m), 264Y (1230 m) and 264P (1650 m).

4. Discussion

Legacy wastewater handling and disposal practices have resulted in persistent secondary salinization at Goose Lake (Reiten and Tischmak, 1993; Rouse et al., 2013; Preston et al., 2014). Produced-water samples from the tank battery in 2009 and 2015 had high TDS and chloride concentrations (121,000 and 145,000 mg/L, respectively); however, these concentrations were on the lower end of chloride concentrations (88,000–199,000 mg/L; median; 168,000 mg/L) from 62 additional samples from the same producing unit (Blondes et al., 2017). These results demonstrate the considerable spatial and temporal variation in wastewater chemistry that can occur within a single oilfield and across different producing areas within the same formation. However, it is likely that wastewater disposed during initial development was similar

Table 2
Location of the screened interval, point attenuation rates, robust standard errors, coefficient of determination (R^2) values, and the year in which chloride concentrations in selected groundwater wells at the Goose Lake study site in Sheridan County, Montana, are predicted to reach Environmental Protection Agency (EPA) acute (860 mg/L) and chronic (230 mg/L) toxicity benchmarks and a local background level (9.5 mg/L) if the relations observed between 1988 and 2018 remain consistent.

Site	Screened Interval	Point attenuation rate/year	Robust standard error	R^2	EPA Acute toxicity	EPA Chronic toxicity	Background
124N*	100% Outwash	0.064^{A**} 0.036^{B}	0.0020 0.0089	0.99 0.65	NA	NA	NA
126B	60% Till 40% Lake	0.028^{B}	0.0017	0.97	2113	2160	2275
264A	60% Outwash 40% Lake	0.037^{B}	0.0043	0.90	2106	2141	2227
264B	60% Outwash 40% Lake	0.034^{B}	0.0048	0.89	2103	2142	2235
264D	60% Till 40% Outwash	0.055^{A}	0.0026	0.98	2045	2069	2126
264Q	100% Outwash	$0.043^{A,B}$	0.0051	0.95	2048	2078	2152

[A,B]Denotes significant differences in point attenuation rate constants.
* Large increases in chloride concentrations in 2018 may indicate potential downgradient migration of brine from an upgradient source area. Given this uncertainty, the year in which water-quality targets would be reached were not calculated for this groundwater well.
** Point attenuation rate calculated from 1988 to 2009 data only.

Table 3
Bulk attenuation rates, robust standard errors, coefficient of determination (R^2) values, previous years' precipitation, and potential downgradient transport distances of chloride emitted from the source zone in 1989, 2005, 2009, and 2018 before dilution Environmental Protection Agency (EPA) acute (860 mg/L) and chronic (230 mg/L) toxicity benchmarks and a local background level (9.5 mg/L) at the Goose Lake study site in Sheridan County, Montana.

Year	Bulk attenuation rate/meter	Robust standard error	R^2	Precipitation in previous year (cm)	EPA Acute toxicity (m)	EPA Chronic toxicity (m)	Background (m)
1989	0.0049	0.00035	0.98	21.7	949	1220	1878
2005	0.0057	0.00078	0.93	30.5	693	923	1480
2009	0.0059	0.00097	0.90	29.6	668	890	1429
2018	0.0053	0.00072	0.89	24.5	673	922	1525

to contemporary wastewater and contained high TDS values dominated by sodium and chloride ions.

Although wastewater contamination is widespread at Goose Lake, there are clear differences in the CI and chloride profiles between the southern and northern groundwater flowpaths (Figs. 3 and 4) that are likely related to different contaminant pathways. In the southern flowpath, CI and chloride profiles show a rapid reduction from peak values near oilfield site 264, indicating the tank battery is the primary source of contamination. Other oilfield sites downgradient are likely associated with minor inputs of wastewater as evidenced by the slight uptick in CI values and chloride concentrations downgradient of oilfield sites 127 and 128. In the northern flowpath, contaminant plumes are associated with oilfield sites 117, 126, and 124 as evidenced by the high CI values and chloride concentrations in adjacent groundwater wells; however, no single source dominates the entire flowpath. Reiten and Tischmak (1993) noted local land owners reported direct discharges of wastewater from oilfield site 124 into wetlands 124D, 124E, and 124F. Given that within each year of sampling the peak chloride concentrations in the northern flowpath occurred in groundwater wells 124H or 124P, which are immediately downgradient from these wetlands, this volume of wastewater may have been greater than that disposed of in reserve pits near the individual oilfield sites. These results highlight the multiple contamination pathways that can exist at legacy energy production sites and the need for detailed site investigations to determine the source(s) and extent of contamination.

Evaluating the spatial and temporal changes in water-quality at Goose Lake requires an understanding of the general hydrogeologic framework in the PPR. Wetlands in the PPR are connected to the shallow groundwater system along a gradient of recharge, flow-through, and discharge wetlands with hydroperiod and salinity generally increasing downgradient (LaBaugh et al., 1987; Winter, 2003). However, annual- to decadal-scale climatic fluctuations constantly evolve the PPR wetland hydroperiod and salinity continuum (Euliss et al., 2004; Euliss and Mushet, 1996; Winter, 2003). Transient groundwater mounds commonly develop adjacent to recharge and flow-through wetlands during drawdown in response to edge-focused groundwater recharge (Arndt and Richardson, 1993; Winter, 2003). Evaporative concentration of dissolved solids is strongly edge focused as summer evaporation results in the upward capillary movement of groundwater and intrasedimentary deposition of salts (Last and Ginn, 2005; Steinwand and Richardson, 1989). Therefore, seasonal drawdown and/or extended dry periods likely results in intrasedimentary evaporitic deposition of wastewater-derived salts along the edges of contaminated wetlands and within previously saturated sediments above contaminant plumes. These salts can then be remobilized into wetland basins or back into the shallow groundwater system during spring runoff, in wet years, or after large recharge events (Reiten and Tischmak, 1993; Preston et al., 2014). This remobilization of salts may complicate remediation efforts and lengthen the time for attenuation to achieve benchmark or background concentrations.

As seen in the groundwater-quality results at Goose Lake, this episodic flushing likely produces temporary pulses of higher salinity superimposed on a general decrease in salinity near wastewater source zones. For example, an 11-year period of near- or above-average precipitation preceded the 1989 sampling followed by a return to drought conditions from 2000 to 2009 (Fig. 2). This likely raised the local water table initially and allowed for considerable flushing of wastewater before stranding salts in the capillary zone as the water table lowered. Chloride concentrations decreased noticeably in nine of the 11 groundwater wells sampled in 2005–06 relative to 1989, yet had increased in six of these wells by 2009 (Fig. 4). During the 2000–09 drought, 2006–07 had near average precipitation, which may have provided enough recharge to remobilize previously stranded salts. Precipitation was highly variable between 2009 and 2018 with more years having above-average than below-average precipitation. Chloride concentrations decreased in 10 of the 16 groundwater wells between 2009 and 2018 with most of these wells located near oilfield sites in the upgradient portions of the flowpaths. In contrast, the six wells with increased chloride concentrations were generally located in the distal portions of the flowpaths (for example 117J, 124P, 264S, and 264T) where chloride continues to be flushed downgradient. From 1993 through 2012, the PPR experienced an extended period of increased precipitation likely unequaled in the preceding 500 years (Mushet et al., 2015). Although this likely raised local water tables and increased the flushing of wastewater at numerous legacy oilfield sites, a return to drought conditions may strand salts in currently saturated sediments that then could become remobilized in future deluge cycles or following large recharge events.

In contrast to groundwater quality, the temporal changes in surface water quality were highly variable. All wetland sampling occurred in years with below-average precipitation (Fig. 2); however, the timing and quantity of precipitation in preceding years strongly influences water levels and water-quality in PPR wetlands (Niemuth et al., 2010; Ouyang et al., 2014; Zhang et al., 2009). Wetland samples in 1989 were collected in late-April or early-May when dissolved constituent concentrations are typically diluted by snowmelt. In contrast, the 2005 samples, which generally had markedly increased chloride concentrations relative to 1989, were collected in mid-June when evapoconcentration increases dissolved constituent concentrations. The 2005 samples were also collected following a longer period of below-average precipitation than the 1989 samples, which can increase salinity in wetlands that do not dry annually (Winter, 2003). Wetland samples in 2009, at the tail end of the 2000–09 drought, were collected in early-May and all samples showed a reduction in chloride concentrations relative to 2005. Finally, chloride concentrations increased in all wetland samples from early-May and late-June in 2015 and all but one wetland sample from early-May in 2018 relative to 2009, whereas groundwater chloride concentrations generally decreased. Therefore, while wetland water quality is useful in identifying wastewater contamination, temporal changes in chloride concentrations appear too dependent on the time of sampling, both seasonally and within a regional climate perspective, to provide a reliable indicator on the movement of contaminant plumes at Goose Lake and, therefore, likely other legacy energy development sites in the PPR.

Chloride concentrations decreased between 1988 and 2018 in the six selected groundwater wells (R^2 values range: 0.89 to 0.99; Fig. 5). These point attenuation rates varied among wells and predict that EPA acute (860 mg/L) and chronic (230 mg/L) toxicity thresholds will be reached in approximately 30–100 and 50–150 years, respectively, whereas background levels (9.5 mg/L) will be reached in 100–250 years (Table 2). The introduction of wastewater likely occurred during energy development in the late 1960s; therefore, the

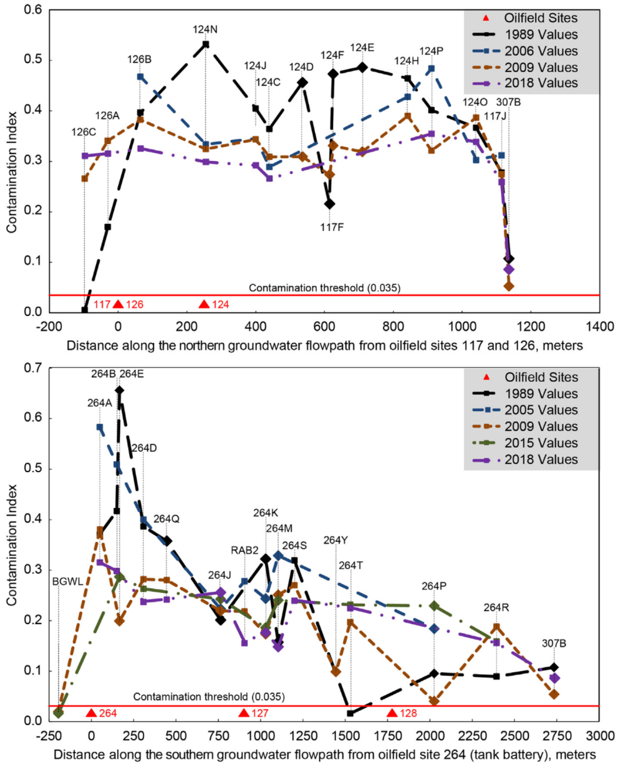

Fig. 3. Temporal Contamination Index values for surface water (wetland; large diamonds) and groundwater (small squares) samples from the northern (top) and southern (bottom) flowpaths by distance from the most upgradient oilfield site at the Goose Lake study site, Sheridan County, Montana, USA. See Fig. 1 for sample locations. In the top panel, distances to sites 117F and 117J are measured from oilfield site 117, whereas distances to all other sites are measured from oilfield site 126.

total predicted time for natural attention is approximately 50 years longer than these model estimates. Given the variation and length of time needed to reach water-quality targets, this work offers an initial estimate of the persistence of wastewater in the PPR and does not attempt to predict the exact year when remediation targets will be reached. However, these results provide the first known quantitative prediction on the natural attenuation rates of chloride contaminated groundwater near abandoned reserve pits in the PPR and support several previous qualitative predictions that leachate generation from reserve pits would continue for tens to hundreds of years (Beal et al., 1987; Murphy et al., 1988; Preston et al., 2014; Reiten and Tischmak, 1993). Furthermore, these predictions apply only to chloride whereas other cations will continue to be released after chloride is removed due to difference in cation exchange affinity (Appelo et al., 1993; Appelo et al., 1990; Valocchi et al., 1981). Therefore, calcium, sodium, potassium, strontium and other cations are likely to be released from near surface sediments for years to decades after chloride has been attenuated.

Attenuation rates derived from field data are generally considered conservative estimates (Chapelle et al., 2003) and are often overestimated (Rittmann, 2004) with additional data improving rate estimates. Although other approaches (e.g., numerical groundwater modeling) have been used to predict contaminant transport rates, we lack data such as sediment porosity/permeability and groundwater flow rates that are necessary to adequately constrain such models and are, therefore, unable to compare the field data-based approach presented here to more quantitative models. Additionally, despite having data spanning 30 years, the predicted point attenuation rate constants were calculated from relatively small sample sizes and the inclusion of 2015–18 changed the rates for some wells. Point attenuation rates derived from 1988 to 2009 data were slightly lower in two wells (126B: 1.6% and 264A: 2.8%), yet considerably greater in three others (264D: 12%; 264Q; 16% and 264B 19%) compared to rates including the 2015–18 data. Furthermore, many legacy sites consist of numerous oil wells and downgradient migration of contaminants from upgradient sources could slow attenuation as observed in groundwater well 124N. Therefore, continued decadal monitoring could validate and/or refine these attenuation rates and reduce the uncertainty in the associated predications.

The significant differences in point attenuation rates are likely related to heterogeneity within the outwash deposits and differences in hydraulic conductivities between different glacial deposits. Point attenuation rates were variable in wells fully or partially screened in the

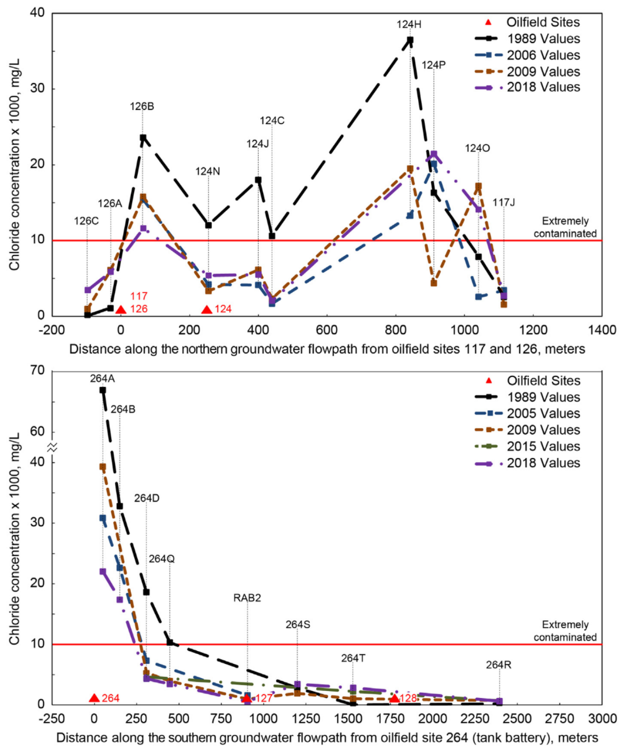

Fig. 4. Temporal chloride concentrations, in mg/L, for groundwater samples from the northern (top) and southern (bottom) flowpaths by distance from the most upgradient oilfield site at the Goose Lake study site, Sheridan County, Montana, USA. See Fig. 1 for sample locations. In the top panel, the distance to site 117J is measured from oilfield site 117, with distances to all other samples measured from oilfield site 126. All samples above the extremely contaminated line also had contamination index values >0.35 except 126B, 124O, and 264B in 2018.

outwash deposits (0.034 to 0.064 yr^{-1}) whereas the rate for 124B (0.028 yr^{-1}), which is screened entirely in glacial till and lacustrine deposits, was the lowest observed and significantly less than two of the wells in the outwash deposits. This is unsurprising as glacial tills generally have much lower hydraulic conductivities than outwash deposits. Considerable emphasis has been placed on reserve pits in permeable outwash deposits as contaminant plumes in these settings can migrate long distances (Beal et al., 1987; Preston and Chesley-Preston, 2015), yet surficial deposits in the PPR of the Williston Basin are predominately glacial tills where natural attenuation of chloride may take considerably longer. For example, the 1989 chloride concentrations in wells 264D (21,760 mg/L) and 126B (24,630 mg/L) were similar; however, background chloride levels are predicted to be reached nearly 150 years sooner in 264D than 126B.

The longevity of secondary salinization from energy development in the PPR is further illustrated by the bulk attenuation rate calculations (Fig. 5; Table 3). Chloride concentrations generally decreased between successive bulk attenuation rate calculations as advective-dispersive transport removed chloride from the source area. As a result, potential distances of downgradient chloride migration until dilution reduces concentrations to EPA acute, EPA chronic, and background levels have decreased by 276, 298, and 353 m, respectively, between 1989 and 2018. However, this equates to respective reductions of only 29, 24, and 18% of the predicted distance of downgradient migration to reach the three water-quality targets over 29 years. Furthermore, several wetlands are still within the 2018 migration distances and will likely receive contaminated groundwater for years or decades. Although no statistical differences existed between the four bulk attenuation rate constants, the variations in individual rates are possibly related to climatic fluctuations. For example, bulk attenuation rates appear positively corelated with total precipitation in the previous year and further supports the remobilization of salts stranded in the capillary zone during drought cycles.

West Goose Lake is a large discharge basin and the likely terminus for the local groundwater flowpaths at Goose Lake. West Goose Lake is further downgradient than the 2018 predicted distance for dilution of chloride to background concentration in the southern flowpath. However, the 2018 chloride concentrations in groundwater wells 124P (21,318 mg/L) and 124O (13,934 mg/L), which are located <200 m upgradient from West Goose Lake, in the northern flowpath were similar to those of 244A and 264B indicating the potential for considerable future discharges of chloride into the lake basin. Chloride will

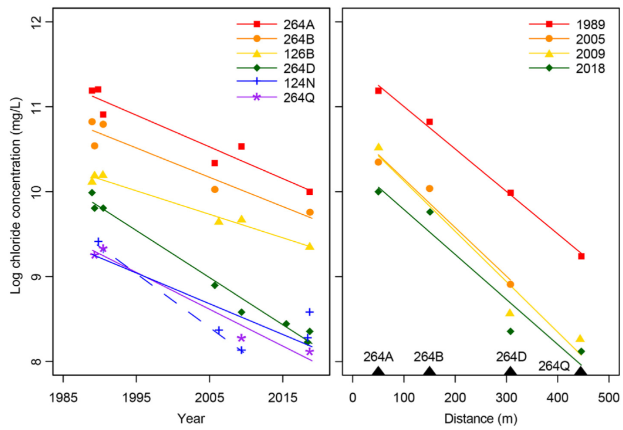

Fig. 5. Fitted linear regression models used to calculate point attenuation constants (left) and bulk attenuation rate constants (right) of chloride in the shallow groundwater system at the Goose Lake study site in Sheridan County, Montana. Dashed blue line in the left panel shows the model fit for 124N calculated from the 1989–2009 data only whereas the solid blue line is for all data (1989–2018).

likely continue to accumulate in West Goose Lake given that elevated groundwater levels in discharge basins often create hydraulic barriers against out-migration of salinity (Van der Kamp and Hayashi, 2009). In the PPR, one of the few potential removal pathways for accumulated chloride in discharge basins is through eolian deflation (removal by wind) of salts that precipitate on the surface (LaBaugh et al., 1998).

There is a growing understanding of the detrimental ecological effects of secondary salinization from energy development. Water levels in flow-through and discharge wetlands are partially sustained by shallow groundwater (Winter, 2003), and the discharge of contaminated groundwater into wetlands coupled with evapoconcentration can increase chloride concentrations seasonally with important biological implications. For example, the chloride concentrations in wetlands 264J and 264K increased roughly four- and twelve-fold (660 to 2800 mg/L and 400 to 4700 mg/L, respectively) between May and September of 2009. Amphibians have highly permeable skin making them especially susceptible to excess salts and other pollutants that can cause direct mortality or sub-lethal effects such as reduced activity, immune function, and size (Dananay et al., 2015; Elphick et al., 2011; Hopkins and Brodie, 2015; Sanzo and Hecnar, 2006). Hossack et al. (2018) documented a 50% reduction in the abundance of boreal chorus frog and tiger salamander larvae in PPR wetlands at chloride concentrations of 298 and 1260 mg/L, respectively. Chloride concentrations in 15 of the 17 groundwater samples in 2018 were >1260 mg/L and all were >298 mg/L. Therefore, evapoconcentration in wetlands receiving groundwater contaminated with wastewater may create ecological traps with these wetlands being habitable to amphibian larvae during the early spring but becoming uninhabitable as chloride concentrations increase throughout the summer. Additionally, wastewater-contaminated PPR wetlands had lower macroinvertebrate taxonomic richness and diversity than uncontaminated wetlands, with chloride concentration being the water-quality parameter most strongly correlated with macroinvertebrate community structure (Preston et al., 2018; Preston and Ray, 2017).

Oilfield wastewaters also has negative effects to terrestrial environments through plant mortality (Keiffer and Ungar, 2001) and altered soil structure (Hoffman and Shannon, 1986). Auchmoody (1989) attributed rapid revegetation of a Pennsylvanian forest following removal of a leaking reserve pit to abundant precipitation and soil flushing. However, spill sites in arid environments can remain unvegetated for years due to elevated soil salinity and deterioration of soil structure (Munn and Stewart, 1989; Murphy et al., 1988; Pichtel, 2016). Soil absorption of sodium from wastewater can decrease hydraulic conductivity, reducing infiltration below levels necessary for plant growth (Hoffman and Shannon, 1986), and create surficial salt crusts that can persist for decades (Keiffer and Ungar, 2002). Several species of salt tolerant halophytes have been shown to accumulate sodium and chloride into plant tissues and reduce soil salinity when grown on wastewater spill sites (Keiffer and Ungar, 2001; Qadir et al., 2006). At Goose Lake, *Salicornia rubra* (pickleweed; a halophytic succulent) commonly grows in several contaminated wetland basins during drought years; however, these plants need to be harvested to facilitate soil bioremediation (Keiffer and Ungar, 2002).

Secondary salinization from energy development is a global phenomenon with wastewater contamination documented on all continents (excluding Antarctica; Johnston et al., 2019) and in biomes ranging from the Siberian tundra (Moskovchenko et al., 2009) to the Amazon rainforest (Moquet et al., 2014). However, several factors (volume and chemistry of wastewater released, surficial geology, precipitation, etc.) influence natural attenuation. Williston Basin wastewater have some the highest recorded TDS values (>450,000 mg/L; Iampen and Rostron, 2000) whereas average TDS values of produced waters from other domestic energy plays are generally lower (Woodford: 30,000 mg/L; Barnett; 80,000 mg/L; Marcellus 120,000 mg/L; Acharya, 2011). Similarly, surficial geology, which control rates of groundwater movement, varies considerably between different energy plays as does precipitation, which is critical for natural attenuation. It is estimated that soils contaminated by wastewaters require at least a 100-fold dilution with fresh water to reduce salts to levels suitable for plant growth (Munn and Stewart, 1989). However, many of the leading domestic energy-producing regions have semi-arid climates that receive <25 cm of rain per year (Keiffer and Ungar, 2002). Therefore, while it is unclear if the persistence of secondary salinization observed in the Williston Basin is transferable to other areas, attenuation rates may be similar in other arid environments (i.e., the Permian Basin in Texas, the Denver Basin in Colorado, or the Green River Basin in Wyoming) and could be evaluated using similar approaches.

5. Conclusions

Energy development at Goose Lake occurred in the late 1960s and resulted in the persistent salinization of surface and groundwater resources. Long-term monitoring has documented the migration of groundwater plumes and associated changes in chloride concentrations, with a general trend of decreases in chloride concentrations in upgradient areas near likely contaminant sources and increases in downgradient areas. For example, although all sites downgradient from oilfield infrastructure were still contaminated in 2018, the number of extremely contaminated sites was reduced from 13 to 2 between 1989 and 2018. However, extremely contaminated refers to sites with chloride concentrations exceeding 10,000 mg/L, a value that is 11.6 times greater than the EPA acute toxicity threshold, and most wetlands in the study area had chloride levels detrimental to aquatic life. Annual and regional climatic fluctuations produced highly variable changes in wetland water-quality that were often decoupled from changes in groundwater-quality, indicating that surface water-quality is an unreliable method to monitor wastewater migration in the PPR. Despite the decreases in chloride concentrations observed across the study period (1988–2018), reducing chloride concentrations in monitoring wells in upgradient areas to pre-spill levels is predicted to take an additional 100–250 years, or longer. Furthermore, it is predicted that chloride flushed from the tank battery in 2018 will migrate nearly 1 km (922 m) downgradient before being diluted below the EPA chronic toxicity benchmark. Roughly one third of wetlands in the PPR are within 1 km of energy development sites (Preston et al., 2014). These results illustrate the persistence of secondary salinization from energy development in the PPR in the absence of remediation activities and highlight the need to reduce and quickly contain future spills to minimize long-term damage to surface and groundwater resources.

Compliance with ethical standards

The authors declare there are no conflicts of interest. This project was fully funded by Federal and State (Montana) government agencies. This article has been peer reviewed and approved for publication consistent with USGS Fundamental Science Practices https://pubs.usgs.gov/circ/1367/). Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Acknowledgements

We thank Sean Lofgren for logistical support and Jeanne Jaeschke, Kalla Fleger, Craig Bowers, Kim Schierenbeck, Jon Reiten, Kevin Chandler, Ken Honeycutt, and Andrew Kretschmer for sample collection and laboratory support. We also thank Andrew Ray and anonymous reviewers for their comments that improved the manuscript. Funding for this project was provided by the United States Geological Survey Toxic Substances Hydrology Program, Amphibian Research and Monitoring Initiative (ARMI), the U.S. Fish and Wildlife Service, Region 6 Inventory and Monitoring Program, and the Montana Bureau of Mines Geology. This manuscript is ARMI contribution no. 688. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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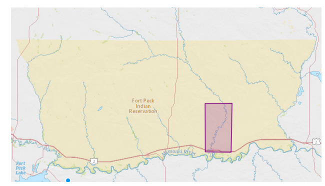
#3992

Wyoming-Montana Water Science Center

Delineation of Brine Contamination in and near the East Poplar Oil Field, Fort Peck Indian Reservation, Northeastern Montana

Brine is a byproduct of crude oil production. Handling and disposal of brine during the last 50 years in the East Poplar oil field has resulted in contamination of not only the shallow Quaternary aquifers, but also the Poplar River. Previous investigations have documented and partially delineated the extent of brine contamination in the East Poplar oil field during the early 1990s. In the 10 years since the last USGS study ended, the extent of contamination has changed and may have grown larger. Brine-plume migration is toward the nearby City of Poplar, which, at present, relies on the shallow Quaternary aquifers as its sole source of water.

Status - Active



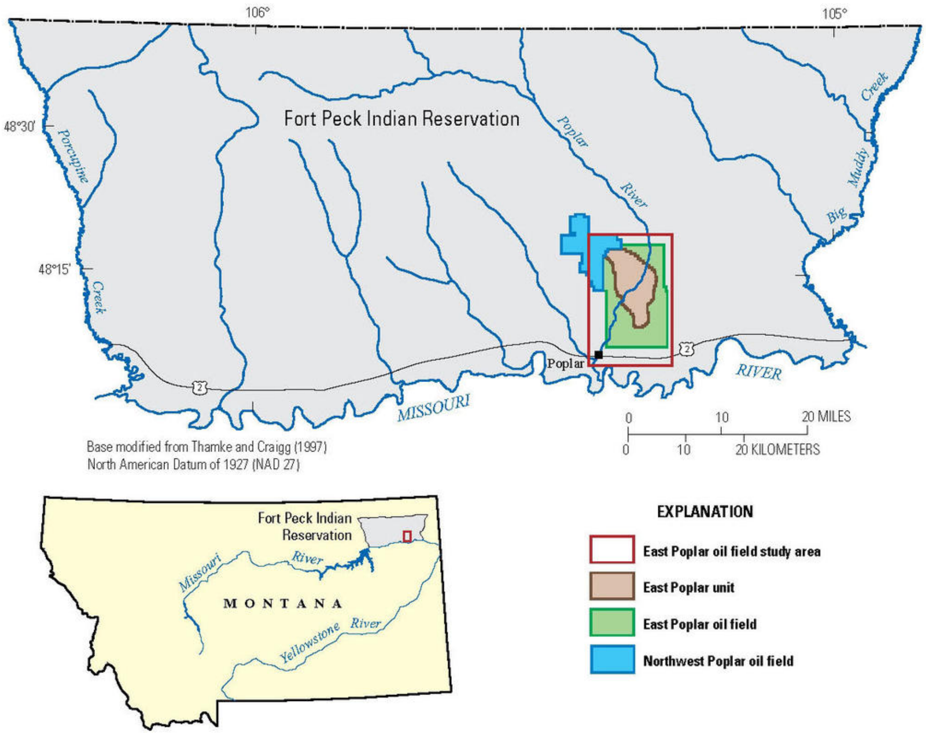
Contacts

Joanna Thamke

Associate Center Director for Studies Wyoming-Montana Water Science Center
Email: jothamke@usgs.gov
Phone: 406-457-5923

Explore More Science:

East Poplar
energy development
Brine
Montana
Streamflow and Groundwater Availability
Water Quality
Characterizing Groundwater



Water Used for Energy Development
Water-Quality Samples
Energy Development and Hydrology
Water

The objective of this project is to more fully delineate brine contamination in shallow aquifers in and near the East Poplar oil field. The project area includes the entire East Poplar oil field, much of the Northwest Poplar oil field and the City of Poplar. Results of the study are detailed in Thamke and Smith, 2014.

Below are other science projects associated with this project.

Date published: DECEMBER 10, 2018
Status: Active

Science Team about Energy and Plains and Potholes Environments (STEPPE)

Brine Contamination to Plains and Potholes Environments from Energy Development in the Williston Basin

Contacts: Joanna Thamke, Brian Tangen, Robert Gleason, Bruce D Smith, Todd Preston, Max Post van der Burg, Seth Haines, Aida Farag, Ph.D., Dave Harper
Attribution: Ecosystems, Water Resources, Fisheries Program, Region 5: Missouri Basin, Geology, Geophysics, and Geochemistry Science Center, Northern Prairie Wildlife

Research Center, Northern Rocky Mountain Science Center, Wyoming-Montana Water Science Center

Below are publications associated with this project.

Year Published: 2017

Characterization and origin of brines from the Bakken-Three Forks petroleum system in the Williston Basin, USA

Brine (also referred to as 'produced water') samples were collected from 28 wells producing oil from the Late Devonian-Early Mississippian Bakken and Three Forks Formations in the Williston Basin of eastern Montana and western North Dakota. The samples were analyzed for major ions, trace metals, stable isotopes, and strontium isotopes. The brines...

Peterman, Zell; Thamke, Joanna N.; Futa, Kiyoto; Oliver, Thomas A.
Attribution: Central Energy Resources Science Center, Energy Resources Program, Region 7: Upper Colorado Basin

View Citation

Year Published: 2016

Chemical and isotopic changes in Williston Basin brines during long-term oil production: An example from the Poplar dome, Montana

Brine samples were collected from 30 conventional oil wells producing mostly from the Charles Formation of the Madison Group in the East and Northwest Poplar oil fields on the Fort Peck Indian Reservation, Montana. Dissolved concentrations of major ions, trace metals, Sr isotopes, and stable isotopes (oxygen and hydrogen) were analyzed to compare...

Peterman, Zell; Thamke, Joanna N.
Attribution: Central Energy Resources Science Center, Energy Resources Program, Region 7: Upper Colorado Basin

Year Published: 2014

Delineation of brine contamination in and near the East Poplar oil field, Fort Peck Indian Reservation, northeastern Montana, 2004-09

The extent of brine contamination in the shallow aquifers in and near the East Poplar oil field is as much as 17.9 square miles and appears to be present throughout the entire saturated zone in contaminated areas. The brine contamination affects 15–37 billion gallons of groundwater. Brine contamination in the shallow aquifers east of the Poplar...

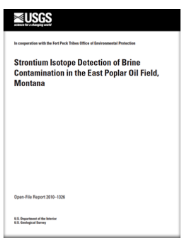
Thamke, Joanna N.; Smith, Bruce D.
Attribution: Energy, Water, Geology, Geophysics, and Geochemistry Science Center, Wyoming-Montana Water Science Center, Water Resources, , Montana, United States of America
View Citation

Year Published: 2014

Borehole geophysical data for the East Poplar oil field area, Fort Peck Indian Reservation, northeastern Montana, 1993, 2004, and 2005

Areas of high electrical conductivity in shallow aquifers in the East Poplar oil field area were delineated by the U.S. Geological Survey (USGS), in cooperation with the Fort Peck Assiniboine and Sioux Tribes, in order to interpret areas of saline-water contamination. Ground, airborne, and borehole geophysical data were collected in the East...

Smith, Bruce D.; Thamke, Joanna N.; Tyrrell, Christa
Attribution: , Geology, Minerals, Energy, and Geophysics Science Center, Geology, Geophysics, and Geochemistry Science Center, Region 7: Upper Colorado Basin
View Citation

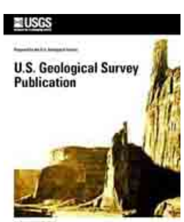


Year Published: 2010

Strontium isotope detection of brine contamination in the East Poplar oil field, Montana

Brine contamination of groundwater in the East Poplar oil field was first documented in the mid-1980s by the U.S. Geological Survey by using hydrochemistry, with an emphasis on chloride (Cl) and total dissolved solids concentrations. Supply wells for the City of Poplar are located downgradient from the oil field, are completed in the same shallow...

Peterman, Zell E.; Thamke, Joanna N.; Futa, Kiyoto; Oliver, Thomas A.
Attribution: , Geology, Minerals, Energy, and Geophysics Science Center, Geology, Geophysics, and Geochemistry Science Center, Region 7: Upper Colorado Basin
View Citation

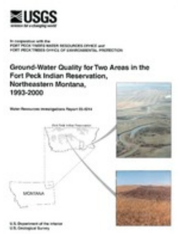


Year Published: 2006

Helicopter electromagnetic and magnetic survey maps and data, East Poplar Oil Field area, August 2004, Fort Peck Indian Reservation, northeastern Montana

This report is a data release for a helicopter electromagnetic and magnetic survey that was conducted during August 2004 in a 275-square-kilometer area that includes the East Poplar oil field on the Fort Peck Indian Reservation. The electromagnetic equipment consisted of six different coil-pair orientations that measured resistivity at separate...

Smith, Bruce D.; Thamke, Joanna N.; Cain, Michael J.; Tyrrell, Christa; Hill, Patricia L.
View Citation


USGS

Ground-Water Quality for Two Areas in the Fort Peck Indian Reservation, Northeastern Montana, 1993-2000

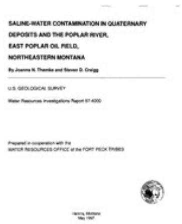
MONTANA

Year Published: 2003

Ground-water quality for two areas in the Fort Peck Indian Reservation, northeastern Montana, 1993-2000

Thamke, Joanna N.; Midtlyng, Karen S.

View Citation


SALINE-WATER CONTAMINATION IN QUATERNARY DEPOSITS AND THE POPLAR RIVER, EAST POPLAR OIL FIELD, NORTHEASTERN MONTANA

U.S. GEOLOGICAL SURVEY

Year Published: 1997

Saline-water contamination in Quaternary deposits and the Poplar River, East Poplar Oil Field, northeastern Montana

The extent of saline-water contamination in Quaternary deposits in and near the East Poplar oil field may be as much as 12.4 square miles and appears to be present throughout the entire saturated zone. The saline-water contamination affects 9-60 billion gallons of ground water. Saline- contaminated water moves westward through Quaternary glacial...

Thamke, J.N.; Craigg, S.D.

View Citation


HYDROLOGIC DATA FOR THE EAST POPLAR OIL FIELD, FORT PECK INDIAN RESERVATION, NORTHEASTERN MONTANA

Year Published: 1996

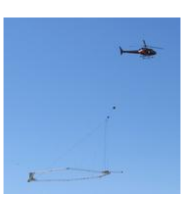
Hydrologic data for the East Poplar oil field, Fort Peck Indian Reservation, Northeastern Montana

This report presents selected hydrologic data for the East Poplar oil field, located in the south-central part of the Fort Peck Indian Reservation in northeastern Montana. Data about the occurrence, quantity, and quality of ground and surface water are presented in tabular form. The tables contain records of privately owned wells (active and...

Thamke, J.N.; Craigg, S.D.; Mendes, T.M.

View Citation

Below are news stories associated with this project.



Date published: OCTOBER 28, 2014

Low-flying Helicopter Surveying Groundwater and Geology in the Poplar River Valley Area, Montana

Citizens should not be alarmed if they see a low-flying helicopter towing a large wire-loop contraption hanging from a cable in the Poplar, Montana area during the next couple of weeks.

Attribution: Energy and Minerals, Region 5: Missouri Basin, Geology, Geophysics, and Geochemistry Science Center

Date published: APRIL 2, 2014

East Poplar Brine-Contaminated Groundwater Plumes Continue to Move

A new report by the U.S. Geological Survey describes the extent and movement of contamination in the East Poplar oil field area in northeastern Montana.

Attribution: Region 5: Missouri Basin

Below are partners associated with this project.

Fort Peck Tribes

#3993

Helicopter Electromagnetic and Magnetic Surveys

By Bruce D. Smith, Robert R. McDougal, Maryla Deszcz-Pan, and Douglas B. Yager

Chapter E4 of

Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado

Edited by Stanley E. Church, Paul von Guerard, and Susan E. Finger

Professional Paper 1651

U.S. Department of the Interior
U.S. Geological Survey

Contents

Plates

[Plates in this report are on accompanying CD-ROM]

Figures

Table

Chapter E4
Helicopter Electromagnetic and Magnetic Surveys

By Bruce D. Smith, Robert R. McDougal, Maryla Deszcz-Pan, and Douglas B. Yager

Abstract

A helicopter electromagnetic and magnetic survey over the Animas River watershed study area has greatly increased the resolution of airborne geophysical data for the study area. The main objective of this chapter is to present geophysical data and maps that can be compared to other data sets and maps of the study area. The results of the survey are useful in mapping surface and subsurface lithology and structure. A brief discussion of selected geophysical anomalies and trends is given. The total-field magnetic and apparent conductivity maps from the helicopter survey are used to interpret near-surface and deep geologic and hydrologic features that can influence ground-water flow. This qualitative discussion supplements a more detailed study using quantitative predictive modeling to characterize structures in the study area.

The total-field reduced-to-pole magnetic map is given at a scale of 1:48,000 superimposed on a topographic base. Derivative maps are given in color shaded relief at a scale of 1:100,000 and include high- and low-pass filtered maps. Qualitatively, a central magnetic low with peripheral magnetic highs caused by younger intrusives characterizes the Silverton caldera. Magnetic lows may be associated with alteration that has destroyed magnetic minerals and (or) may be associated with reverse magnetization.

Helicopter-borne measurements from five frequencies and two system geometries were used to compute apparent electrical conductivities. The pre-processed electromagnetic data have high noise along flightlines due to helicopter flying limitations caused by the high rugged terrain. The apparent conductivity map for the intermediate frequency (and depth of investigation) is given at 1:48,000 and again on a topographic base. The apparent conductivity is also presented as color shaded-relief maps at a scale of 1:100,000 for three frequencies and one system configuration. These maps reflect variations of the subsurface electrical conductivity ranging in depth from a few meters to on the order of 60 meters. The Silverton caldera is generally characterized by conductivity lows in the central part ringed by conductivity highs. Conductivity highs can be related to electrically conductive surficial rocks and sediments as well as deeper bedrock alteration both in narrow zones along drainages and in broad areas of hydrothermal alteration.

High apparent conductivities near one mine-waste pile suggest near-surface flow paths and a source for high dissolved solids where high-sulfide mill tailings have been removed after the helicopter survey. The youngest dacite-rhyolite intrusives show different types of magnetic and electrical properties that may be associated with different types of lithologic and ground-water regimes. Apparent conductivity maps suggest a northwest-trending structural zone along Cement Creek and extending toward Ohio Peak that may influence ground-water flow.

Introduction

An airborne electromagnetic and magnetic survey was flown over portions of the Animas River watershed to supplement other geologic, geochemical, and hydrologic studies that were carried out for the collaborative study. New airborne geophysical data were needed because the only available data for the study area were total-field magnetic and radiometric data with a flightline spacing of 2 miles (Oshetsky and Kucks, 2000). In general airborne geophysical methods provide data to interpret subsurface lithology, structure, and in some cases electrically conductive ground water. Smith and others (2000) have described how airborne geophysical surveys can be applied to abandoned mine land studies. McCafferty and others (2004) have demonstrated the application of quantitative class modeling of airborne electromagnetic and magnetic survey data in predictive mapping of acid-neutralizing terrains in the Boulder River watershed, Montana.

One main focus of the Animas River watershed AML study has been the source, transport, and fate of acid water derived from mining activities and from areas that have not been mined. Though much of the ground-water flow is through streams, an unknown amount flows through the subsurface colluvium and bedrock of the study area. Little specific information about the nature of this subsurface flow exists, although Huntley (1979) and Caine (2003) have made some generalizations on a watershed scale. Ground and airborne geophysical studies provide data that can be used to interpret subsurface heterogeneities that can be related to the origin and flow of acid water.

Purpose and Scope

The purpose of this investigation is to present the results of a helicopter electromagnetic and magnetic (HEM) survey flown over the Animas River watershed study area. The results of the survey are useful in mapping surface and subsurface lithology and structure. Geophysical maps from the airborne geophysical surveys are given in plates 3 and 4 of this volume. The objectives of the study are to:

- Present the airborne geophysical data in maps that can be compared to other maps from the AML study
- Describe data collection and reduction procedures for the airborne survey
- Present derivative maps that can be used in interpretation of subsurface geophysical features
- Provide some interpretation of geophysical anomalies in terms of lithology, structure, and possible hydraulic features.

Geophysical Surveys

A regional airborne survey of the study area was flown as part of the National Uranium Resource Evaluation (NURE) with E.-W. flightlines 400 feet[1] above ground with 2 mile spacing (Aero Service, 1979). Oshetsky and Kucks (2000) used these data and other airborne surveys to compile a statewide total magnetic field grid at 1,000 feet above ground level with a cell size of 500 m square. Figure 1 shows a portion of this regional airborne magnetic map for the northwestern part of the San Juan volcanic field with the main drainages of the Animas River watershed study area (from west to east, Mineral Creek, Cement Creek, and Animas River). Locations of three detailed helicopter geophysical surveys that have been flown in the Silverton and Lake City caldera areas are shown as boxes in figure 1 and in figure 2 with more detail. The detailed surveys are located over the Lake City caldera (Red Cloud and Lake City surveys in fig. 2, not discussed here) and the Silverton caldera (Animas survey in fig. 2; see following discussion). The regional airborne magnetic survey shows that the Lake City caldera is generally characterized by magnetic highs, in contrast to the older Silverton caldera, which is characterized by a central magnetic low. Grauch (1987a) observed that the magnetic expression of the Silverton Volcanics (postcaldera volcanic flows and volcaniclastic sediments) is low within the Silverton caldera and high within the Lake City caldera. The contrasting magnetic expression within this unit is due to variable natural remanent magnetization and to alteration.

[1]Measurements originally made and reported in feet and miles are retained here in their original units for clarity and to avoid misstatement of precision in conversion. To convert feet to meters, multiply by 0.3048; to convert miles to kilometers, multiply by 1.61.

The Red Cloud survey (fig. 2) was flown as part of the NURE program (High Life Helicopters, 1983) with N.–S. lines spaced 0.25 mi (miles) using spectral radiometric and total-field magnetic systems. The Lake City helicopter survey flown (fig. 2) as part of USGS programs (High Life Helicopters, 1981) used 0.3 mi flightline spacing, N.–S. lines, 400 ft above ground. Grauch (1987a, b) has interpreted the Lake City survey with emphasis on effects of the rugged terrain on the magnetic data.

The Animas helicopter electromagnetic and magnetic (HEM) survey was conducted over part of the Animas River watershed (fig. 3) during late May 1999 (Smith and others, 2000, 2004) under a contract to the U.S. Geological Survey. The objective of this survey was to map subsurface lithology and structure that could be important in geologic, structural, and hydrologic studies related to the Animas River AML study. The survey flightline spacing was 200 m and 400 m, as shown in figure 3. Closer flightline spacing was used in the western part of the survey area in order to improve resolution in the area of Mineral and Cement Creeks. In addition, flightlines were flown along South Fork Mineral Creek, Mineral Creek, Cement Creek, and the upper Animas River. These flightlines were done to obtain more detailed data along the drainages where tracer studies were planned (Kimball and others, this volume, Chapter E9). They were flown at a more constant elevation than was possible with the north-south flightlines. The stream valleys are deep and narrow, which makes it difficult for a helicopter to maintain constant elevation when crossing the terrain. Four east-west flightlines were flown as tie lines for processing the magnetic field measurements.

The nominal helicopter flight height was specified to be 60 m above terrain. In practice the flight elevation varied between 60 and 90 m due to flight safety considerations in the extremely rugged terrain. The geophysical electromagnetic (EM) and magnetic system was towed in an 8 m long torpedo-shaped “bird” at a distance of about 30 m below the helicopter. The instrumentation included a high-precision GPS system that provided a positional accuracy of about 5 m. Barometric and radar altimeters provided additional data on the elevation. The position of the flight path provided by the GPS was checked with video records from the flight path video camera.

Magnetic System and Data Processing

A cesium split-beam total-field magnetic sensor was used for the magnetic field measurements. The in-flight sensitivity of the system was 0.001 nanotesla (nT) with a recording rate of 0.1 second. The sensor tolerated gradients up to 10,000 nT/m, and the dynamic range was 20,000 to 100,000 nT. A heading test after system installation and prior to surveying showed a maximum variation of ±0.92 nT. A total-field magnetic base station placed within the survey area used a sensor with the same specifications as the airborne sensor. No magnetic storms occurred during the survey.

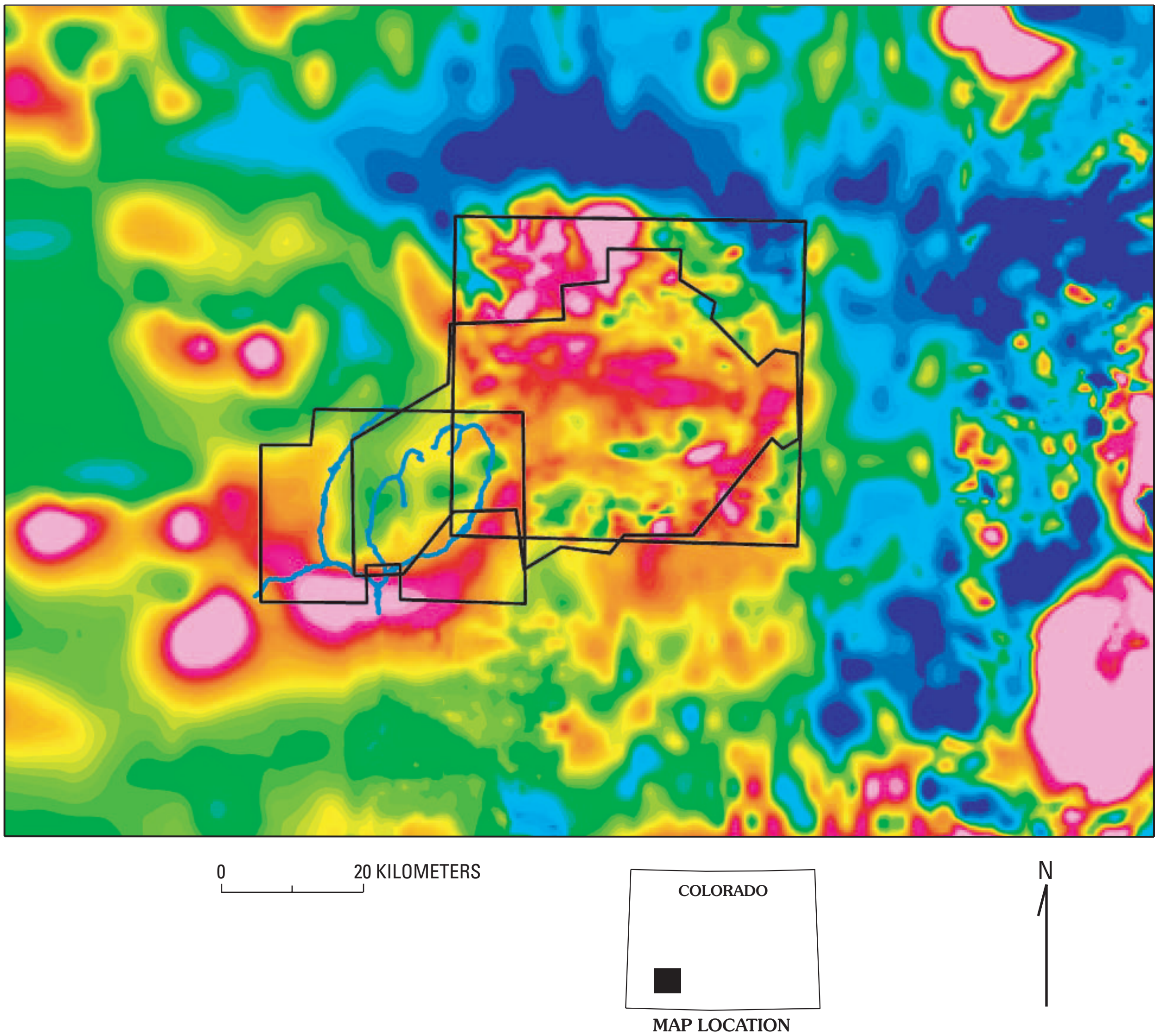


Figure 1. Total-field magnetic map of a region surrounding the Animas River watershed study area. Data are a subset from the compilation of Colorado aeromagnetic data by Oshetski and Kucks (2000). Warmer colors (reds), magnetic highs; cooler colors (blues), lows. The digital grid has a cell size of 500 m square. Boxes indicate areas where detailed helicopter surveys were done (see fig. 2 for scale). Blue lines, main drainages of the study area (see fig. 3), from west to east, South Fork Mineral Creek, Mineral Creek, Cement Creek, and Animas River.

The in-flight magnetic field data were corrected for diurnal variations using the base station records. The International Geomagnetic Reference Field (IGRF) was computed and removed along each flightline. The magnetic data were gridded using minimum curvature methods with a 40 m square cell size for the western part of the survey area and an 80 m cell size for the eastern part of the survey (fig. 1). The eastern grid was resampled to a 40 m cell size and merged with the western grid.

The IGRF-corrected total-field magnetic grid was filtered using a reduction-to-pole (RTP) filter implemented in the USGS potential field programs (Phillips, 1997; Phillips and others, 2003). This filter transforms the magnetic field so that anomalies are positioned directly above the causative body. This filtering will produce a correct positioning of the magnetic responses as long as (1) the causative source of the magnetic anomaly does not have a strong natural remanent magnetization and (2) the magnetization is predominantly all induced in the direction of the current main magnetic field. Although some rock units in the Silverton caldera exhibit remanent magnetization (Grauch and Hudson, 1987), the magnetization intensities and directions are low and within a range collinear with the present-day magnetic field.

The RTP magnetic grid was also filtered to separate short and long spatial wavelengths through a process termed matched filtering (Syberg, 1972). USGS computer field programs by Phillips (1997) were used to do this processing. The short wavelength anomalies approximate sources that are

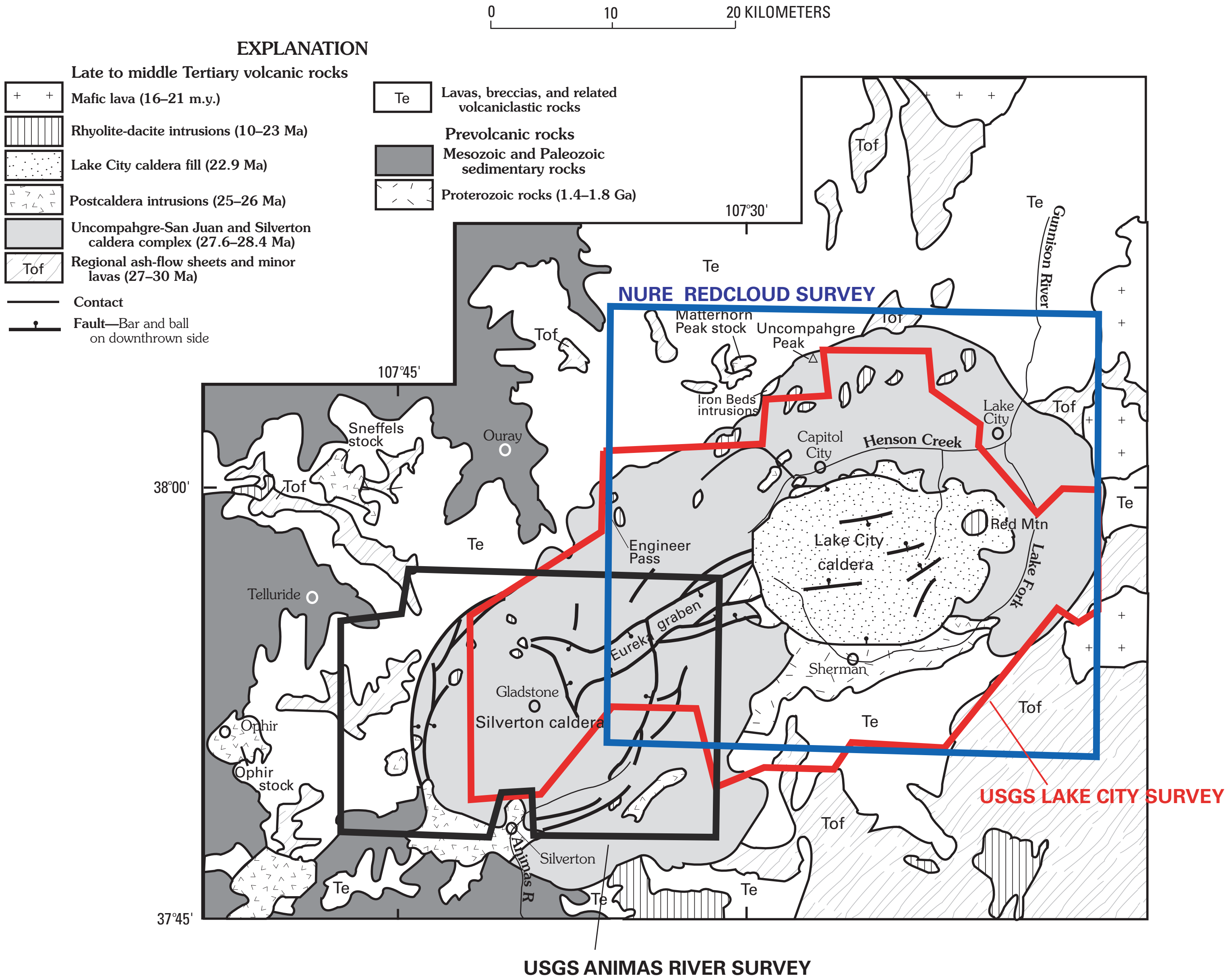


Figure 2. Generalized regional geology of Silverton and Lake City calderas, southwest Colorado. Heavy solid line, boundary of detailed aeromagnetic surveys flown in area. Magnetic maps from USGS Animas survey are discussed here. Geologic index map modified from Bove and others (2001). Geologic map for the Animas survey area is in Yager and Bove (2002) and plate 1 of this volume.

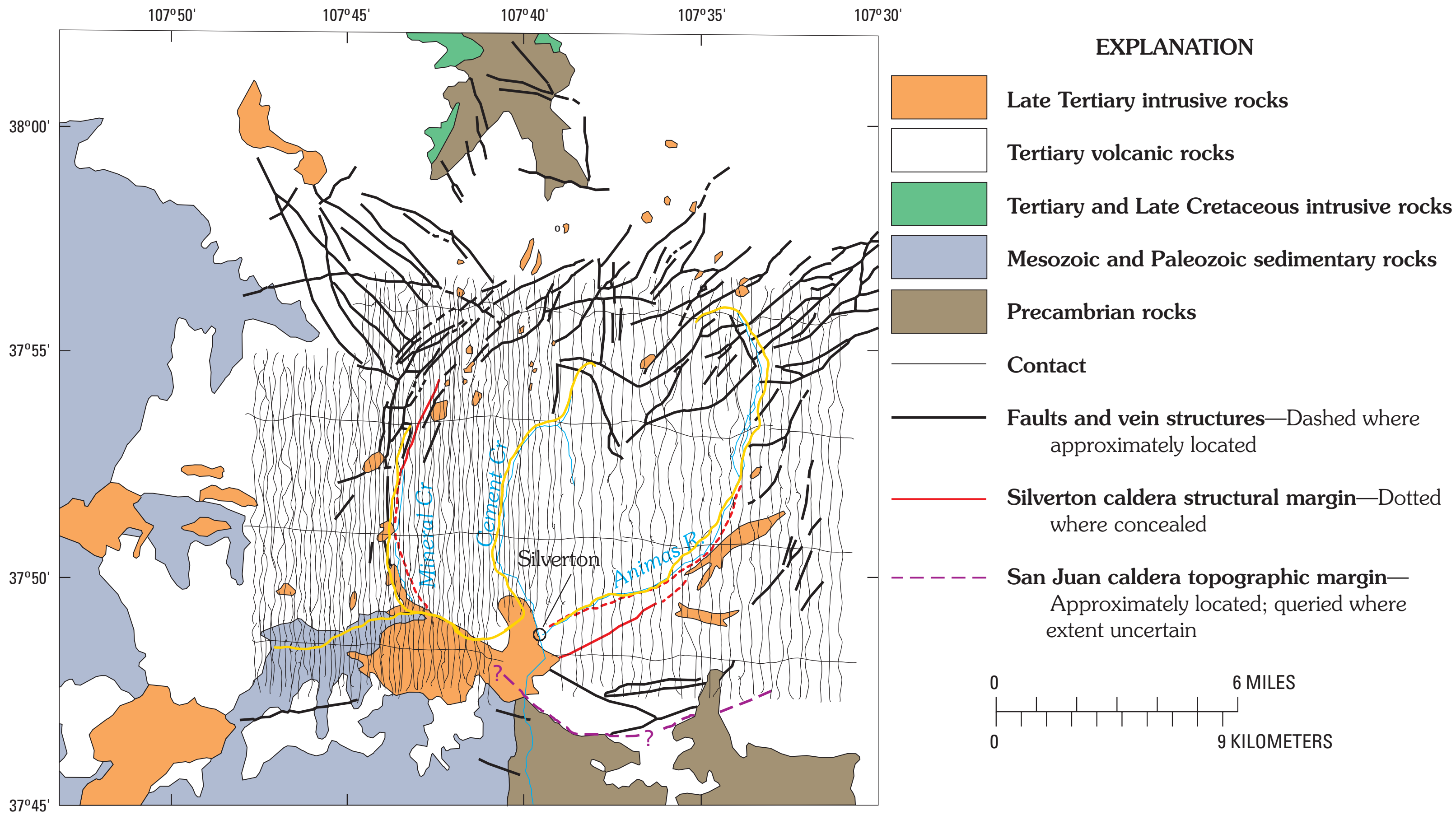


Figure 3. Generalized geology of Animas River watershed study area, southwest Colorado. Thin north-south black lines, flight path of helicopter in main part of survey area. East-west lines, tie lines. Yellow lines are flightlines flown along selected drainages. Major tributaries to the Animas River are shown in addition to major Tertiary volcano-tectonic structures related to the Silverton and San Juan calderas. Figure is modified from Casadevall and Ohmoto (1977).

in the upper 200 m beneath the topographic surface. The map produced from this data is termed a “high-pass” magnetic anomaly map and should correspond most closely with the sources of anomalies from the electromagnetic survey.

A matched filter was also applied, using the same programs (Phillips, 1997; Phillips and others, 2003), to enhance long wavelength anomalies that could represent sources at depths of more than 1,300 m. This map is termed a “low-pass” magnetic anomaly map.

Electromagnetic System and Data Processing

The EM system consisted of five coil pairs operating at different frequencies. Three of the coil pairs were oriented in a horizontal coplanar (CPL) configuration and the other two in a vertical coaxial (CXL) configuration. Table 1 gives the frequencies for each of the coil configurations. The frequencies were set before the survey was started and were maintained during flight operations.

Data from the CXL configuration, normally used in exploration for dike-like conductors, are very susceptible to in-flight noise and have not been used in this study. The CPL coil pairs are best suited to mapping of subsurface electrical conductivities.

Care was taken to establish calibration levels for the electromagnetic system both before and during the survey. However, in post-processing by the USGS, absolute levels of the EM channels were found to be unreliable. A number of different approaches (Fitterman, 1999) were used to adjust the levels to produce agreement with ground electromagnetic measurements. None of these methods could entirely correct the data. The data presented here have not been adjusted beyond the leveling done by the contractor who conducted the airborne survey. Quantitative interpretations beyond the qualitative interpretation presented here will require additional leveling of the HEM survey data.

The contractor used the EM measurements at each frequency to calculate apparent resistivity using the method described by Fraser (1978). The method estimates the resistivity of a homogeneous half space based on the EM measurements, hence the term apparent resistivity. For the purposes of this study, the apparent resistivity (ρ, ohm meters) was converted to apparent conductivity (σ, millisiemens per meter) where $\sigma=1{,}000/\rho$. Maps of apparent conductivity presented here show high conductivities in warmer colors in order to emphasize such features.

Table 1. Frequency and coil orientation for the electromagnetic system.

Frequency (Hz)	Configuration
886.00	Coaxial
984.00	Coplanar
4,836.00	Coaxial
4,310.00	Coplanar
32,960.00	Coplanar

Map Compilation

The digital raster graphic topographic base map was scanned from a green-line topographic base. The base is the same digital map as used for the geologic map of the Animas River watershed study area and vicinity (Yager and Bove, 2002, and Yager and Bove, this volume, Chapter E1, pl. 1). All of the digital data were projected to the Universal Transverse Mercator (UTM zone 13) geographic projection. The digital database used a 2.5 m resolution and was resampled to 8 m for the digital version of the base. All of the airborne geophysical data used this same projection. The positional accuracy of the HEM survey is on the order of 5 m in the horizontal position and 10 m in the vertical position based on the post-processing of the differential global positioning system (GPS).

Magnetic and Electrical Properties

Magnetic Responses

The magnetic response of the volcanic rocks is controlled by the amount of magnetic minerals, primarily magnetite and to some degree ilmenite, maghemite, and titanomagnetite present in the rocks (Telford and others, 1978). Pyrrhotite is a magnetic iron sulfide mineral that is common in some sulfide mineral deposits but does not occur in abundance in the mineralized systems in the study area. The amount of magnetic minerals in rocks determines the magnetic susceptibility and thus its strength of magnetization. Rocks with a high susceptibility will produce a strong dipolar magnetic response (Telford and others, 1978). Natural remanent magnetization (NRM) also affects the amplitude of observed magnetic anomalies depending on its direction and intensity. Often the direction of the NRM is opposite that of the induced magnetization, resulting in a lowering of magnetic response or reversal of the dipolar signature. Grauch and Hudson (1987) and Gettings and others (1994) have examined the NRM and magnetic susceptibility of the volcanic rocks in the Silverton and Lake City calderas. The nature of NRM has been discussed previously in regard to processing of the total-field magnetic data. As is typical of many volcanic terrains, both NRM and magnetic susceptibility are highly variable both within and between stratigraphic and lithologic units. Basic igneous rocks have high magnetization, with granite, andesite, and rhyolite having generally lower magnetization. Volcanic rocks in general have higher magnetization than sediments unless the sediments contain magnetite. Hydrothermal alteration of volcanic rocks is likely to reduce their magnetite content (Telford and others, 1978). Several different types of alteration have been observed and mapped in the study area (Bove and others, 2000; McDougal and others, this volume, Chapter E13).

Electromagnetic Responses

Several factors control the electrical conductivity of rocks (Telford and others, 1978; Olhoeft, 1985), and these can be generalized for the geologic setting of the study area. In general, introduction of clay minerals (including zeolites) tends to increase the electrical conductivity of rocks. Both hydrothermal alteration and weathering processes of volcanic rocks in the area can produce clay minerals. Metallic veins, particularly massive sulfides such as pyrite, can drastically increase the electrical conductivity. Ground water having high dissolved solids can increase measured electrical conductivity. Sediments in valley fill may be much more conductive than bedrock due to silt (particularly with high organics) and clay mineral content and water with high dissolved solids. However, the processes that create valley fill may also weather the bedrock under the valleys, reducing the electrical contrast between rock units. Some types of glacial sediments, such as moraines, may have high clay content and thus high electrical conductivity.

Areas of low conductivity (high resistivity) can be caused by alteration that causes silicification of porous media. McDougal and others (this volume) have analyzed the electromagnetic data to map areas of low conductivity that may be associated with fracture and fault systems. In general, any process that decreases the permeability and porosity of rocks tends to increase the resistivity or lower the conductivity. This variation is related to observation that the amount and nature of pore fluids have an enormous effect on the electrical resistivity of rocks (Olhoeft, 1985). Thus rocks above the water table generally have a low conductivity.

Discussion

Geophysical maps from the helicopter magnetic (pl. 3) and electromagnetic (pl. 4) survey are given at scales (1:48,000) comparable with the geologic map of the study area (Yager and Bove, 2002, and pl. 1, this volume). The purpose of the following section is to illustrate interpretations of specific anomalous features that are relevant to the Animas River watershed AML study. A detailed discussion of the airborne geophysical data is given by McDougal and others (this volume) in terms of quantitative predictive modeling designed to characterize structural and lithologic terrains.

Magnetic Maps

Plate 3 gives the color total-field magnetic map for the Animas River watershed study area superimposed on a topographic base. The 1:48,000-scale total-field reduced-to-pole (see processing section) magnetic map can be compared directly to the geologic map of the study area given by Yager and Bove (2002, and this volume, pl. 1). The color shaded-relief map is shown for the total-field magnetic survey data in figure 4. The shading is shown with a sun angle from N. 45° E., which emphasizes trends in the conjugate (N. 45° W.) direction.

The reduced-to-pole map (pl. 3 and fig. 4) generally shows that the central part of the Silverton caldera is defined by magnetic lows relative to the margins. The high-pass magnetic map (fig. 5) shows features that should be from sources at depths similar to the EM data. The low-pass magnetic map (fig. 6) shows longer wavelength magnetic responses that are caused by sources that are deep or broad and shallow. Specific features of each map are discussed in following paragraphs and also by McDougal and others (this volume).

Magnetic Features

Magnetic features are shown in figure 7, where letters identify linear features and numbers identify anomalies. Anomaly 10 in figure 7 is a discrete magnetic low. Narrow high magnetic anomalies that occur in the east and north part of anomaly 10 may be dikes. The magnetic low may extend farther to the east beyond the dikes. Rocks that are either reversely polarized or intensely altered (where the magnetic minerals have been destroyed) are possible sources for the magnetic low.

Linear feature P (fig. 7) is located on the southeast of magnetic anomaly 10. Interpreted linear features Q, R, and S in the magnetic map (fig. 7) may indicate structures that cross the caldera boundaries. Such structures could influence ground-water flow directions in the caldera ring fault system.

The magnetic high anomalies labeled 15 (fig. 7) are associated with the Sultan Mountain stock (Yager and Bove, 2002; this volume, pl. 1), one of the Tertiary intrusives in the San Juan caldera complex. The strong magnetization suggests that this late Tertiary intrusive complex is unaltered.

The area of peak 3,792 m, between Middle and South Forks Mineral Creek (Yager and Bove, this volume; Bove and others, this volume), is characterized by a magnetic high (anomaly 16, fig. 7). The magnetization is not as intense as the magnetization of the Sultan Mountain stock.

Magnetic high anomalies occurring at the south edge of the Silverton caldera are labeled 11 (fig. 7). The magnetic highs correlate with topographic highs and are likely due to the relatively flat lying Henson Member of the Silverton Volcanics. The magnetic rocks of the Sultan Mountain stock have been mapped just north of the Animas River; so some of the high magnetic anomalies just to the northwest of the junction of the Animas River and Cement Creek may be due to this source.

Several small isolated magnetic high anomalies are labeled 12 in figure 7. Farther east, in the Lake City caldera, this type of magnetic anomaly is associated with late Tertiary intrusives, which have been discussed in detail by Bove and others (2001). Anomaly 13 (fig. 7) is a magnetic low in the upper Animas River basin. This magnetic low is not associated with nonmagnetic valley fill, but is more likely caused by volcanics that have very little magnetite (perhaps due to alteration) or are reversely polarized.

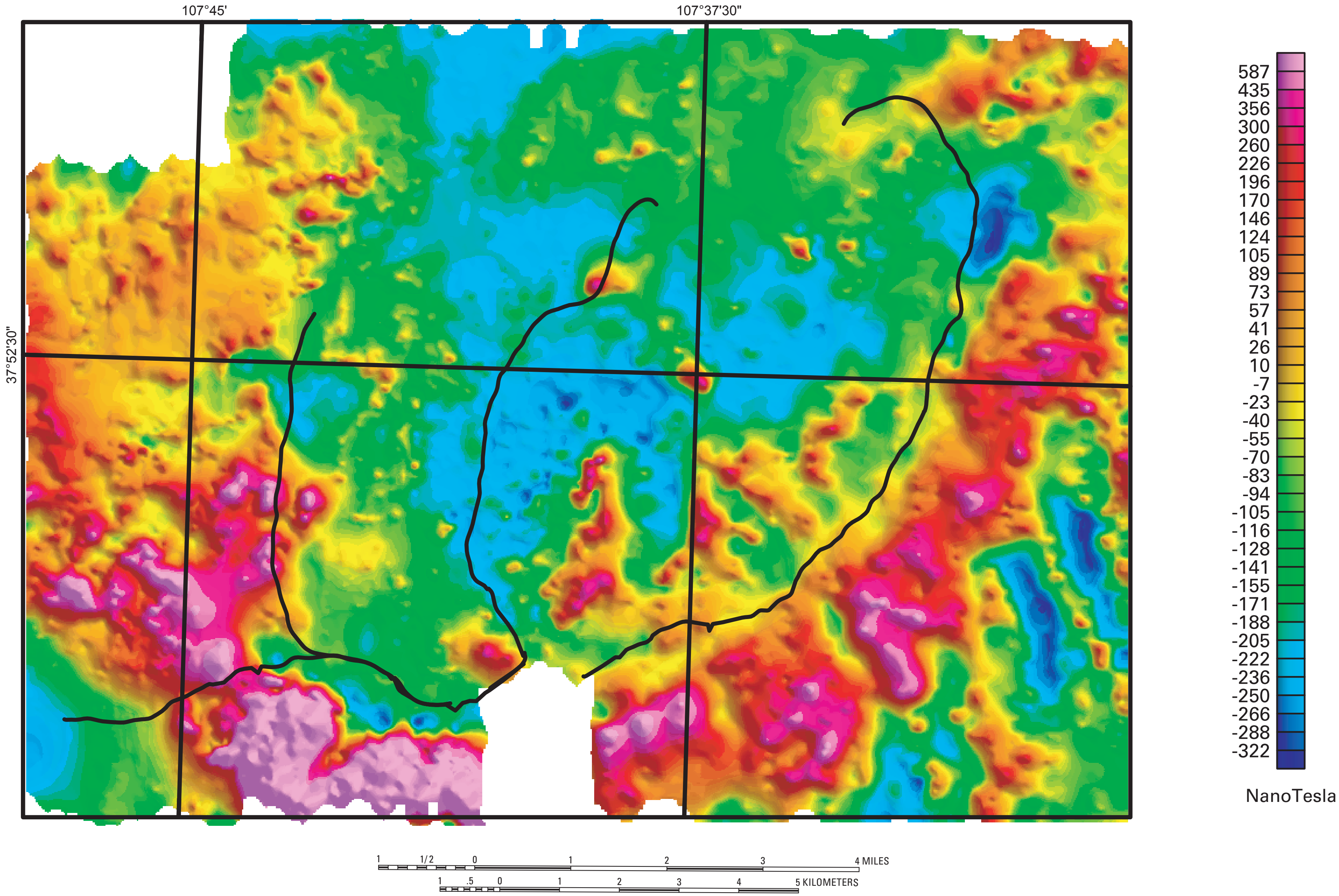


Figure 4. Color shaded-relief reduced-to-pole total-field magnetic map of Animas River watershed study area. Color scale bar shown at right. Sun direction is from northeast. Black line, flightline flown along selected drainage as shown in figure 3. Figure is of same area as shown in the 1:48,000 reduced-to-pole magnetic map (pl. 3).

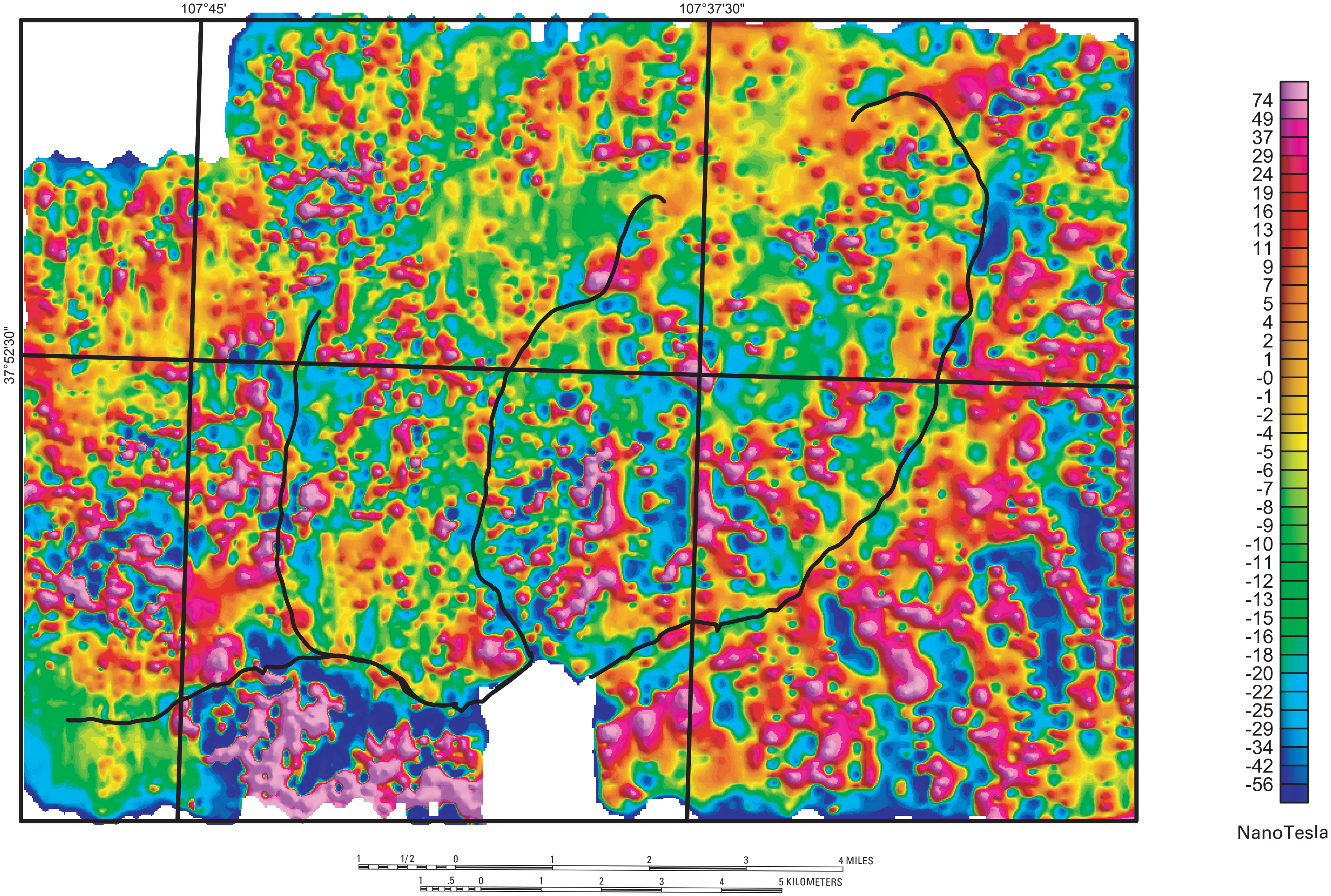


Figure 5. Color shaded-relief high-pass filtered RTP map for Animas River watershed study area. Sun direction is from northeast. Black line, flightline flown along selected drainage as shown in figure 3. Figure is of same area as shown in the 1:48,000 reduced-to-pole magnetic map (pl. 3).

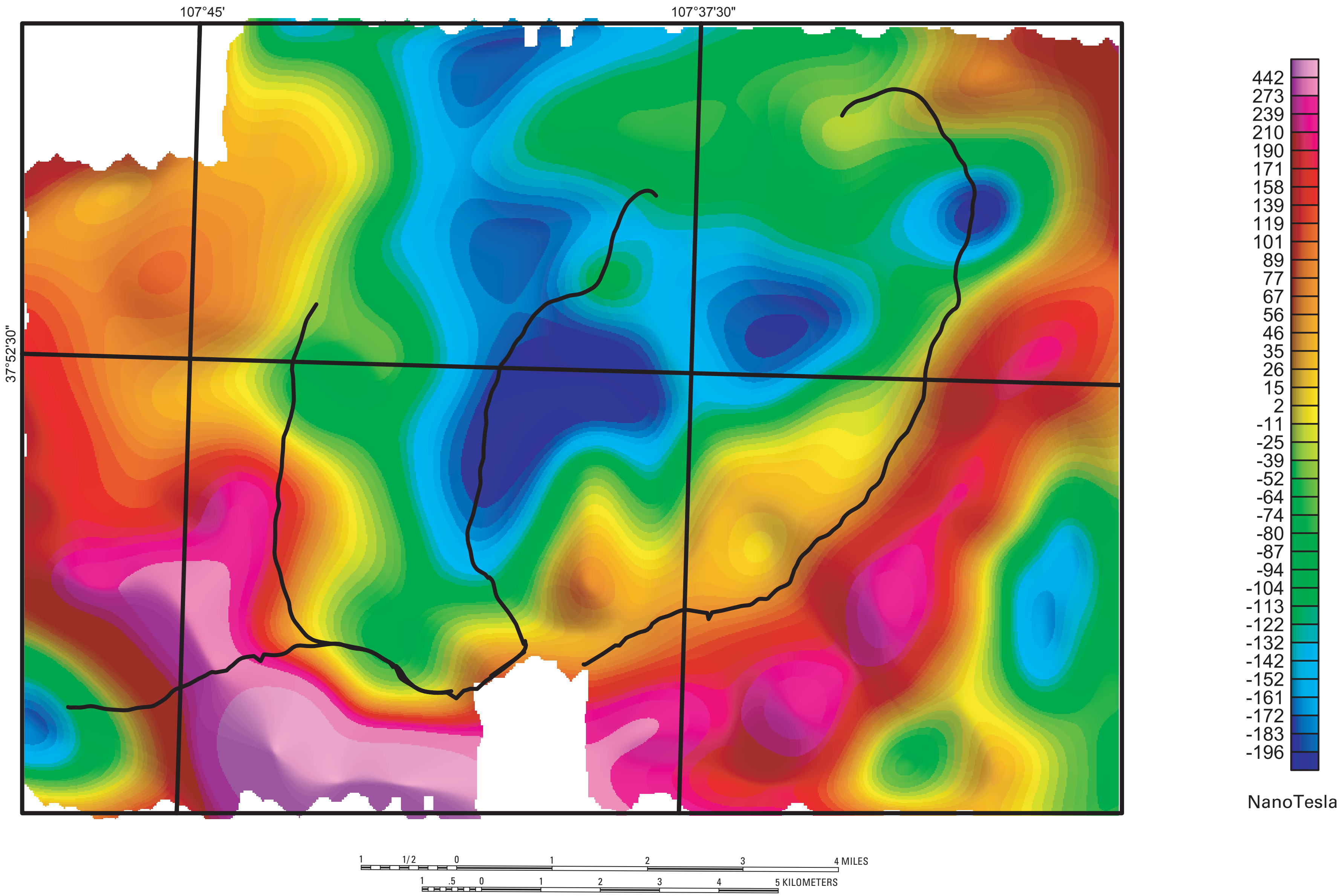


Figure 6. Color shaded-relief low-pass filtered RTP map for Animas River watershed study area. Sun direction is from northeast. Black line, flightline flown along selected drainage as shown in figure 3. Figure is of same area as shown in the 1:48,000 reduced-to-pole magnetic map (pl. 3).

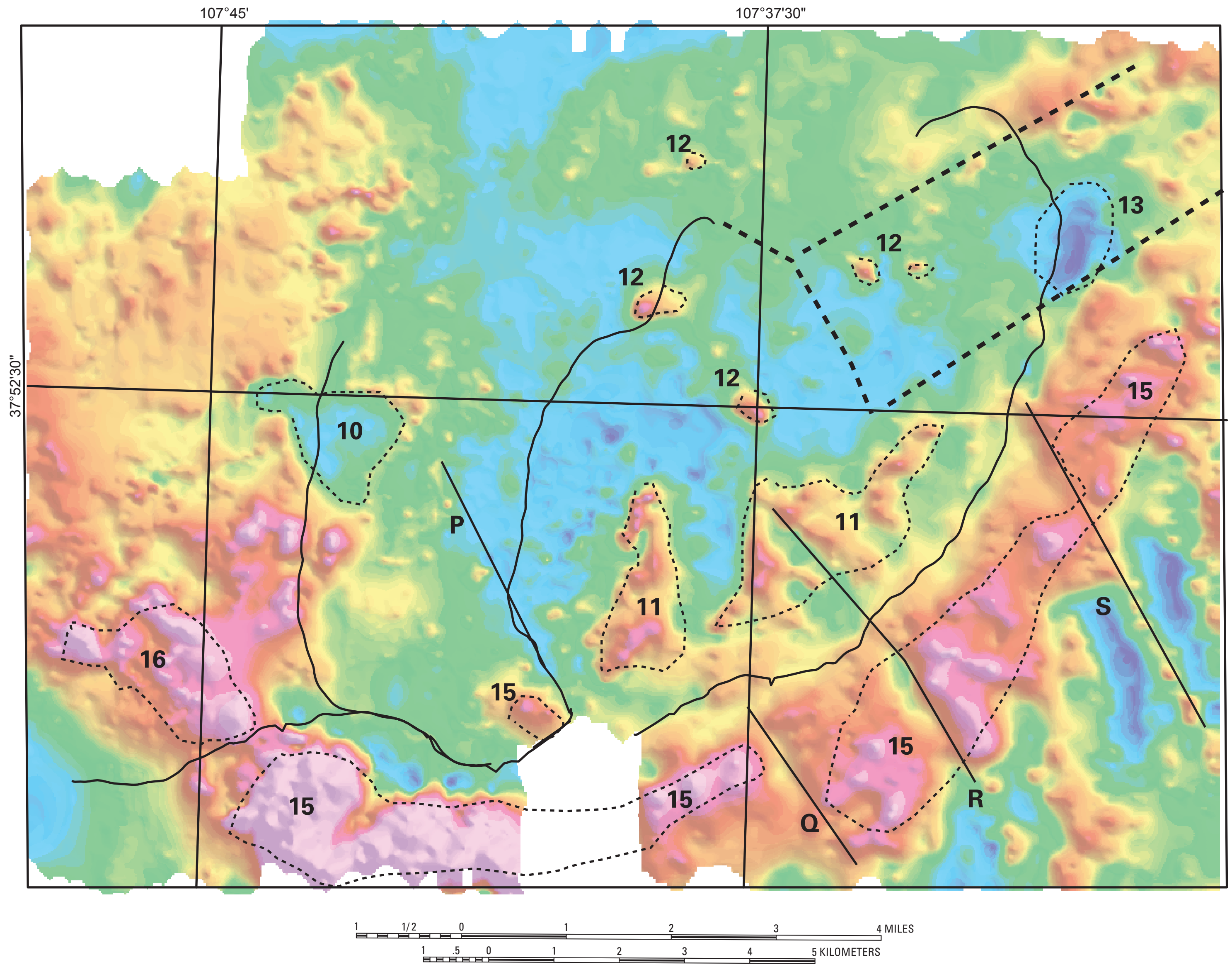


Figure 7. RTP magnetic map showing selected anomalous features. Linear features (bold letters and black lines) are selected from a number of features identified by McDougal and others (this volume). Magnetic anomalies (numbers) have been selected to characterize general geologic features. Color shaded relief from figure 4 is shown as background. Curving solid black line, flightline along selected drainage. Heavy dashed line is general outline of Eureka graben.

Apparent Conductivity Maps

Plate 4 shows apparent conductivity in the Animas River watershed study area. The 1:48,000-scale color apparent conductivity map can be compared directly to geologic maps of the study area (Yager and Bove, 2002; Yager and Bove, this volume, pl. 1). The intermediate frequency (4,310 Hz) has been used for the main map because it best represents general characteristics of the electrical structure of the study area.

Color shaded-relief (CSR) maps are commonly used to emphasize trends. Figures 8–10 show CSR maps of apparent conductivity for the three horizontal coplanar coil pairs from high to low frequency. The sun illumination angle is N. 45° E. with an inclination of 45°. Thus, features trending northwest are emphasized. In these maps, the high conductivities are shown in warm colors (reds) that correspond to low resistivities. The general structural trends described by Burbank and Luedke (1969) are northeast, north, and northwest. Maps using several different illumination angles were examined, and the northeast illumination direction was qualitatively the best to emphasize trends discussed herein. However, this illumination angle does not emphasize the northeast-trending structures described by Casadevall and Ohmoto (1977), such as the Eureka graben. The use of particular color scales (resistivity or conductivity) depends on the type of geophysical features that are being highlighted. In this discussion, conductive features are highlighted using warmer colors. The color scale for each frequency is stretched to yield a consistent scale between maximum and minimum values of apparent conductivity. Note that this results in specific colors on each map representing different apparent conductivity.

The highest frequency (fig. 8) has the greatest spatial frequency variation due to more system noise from in-flight altitude variations and also due to large variations in shallow geology. At this frequency, the depth of investigation is only a few meters. Areas of high anomalous conductivity (fig. 8) are generally located in the northwest, between Cement and Mineral Creeks, and in the area of peak 3,792 m. The south end of the Eureka graben (fig. 3) is associated with a shallow high conductivity anomaly (fig. 8). A high conductivity anomaly also lies along the northern part of the Animas River.

The intermediate-frequency apparent conductivity map (fig. 9) has less high spatial frequency variations due to less system noise, greater spatial averaging, and deeper penetration. The depth of penetration at this frequency is on the order of 30–40 m. High apparent conductivities (fig. 9) are generally in the same areas as for the higher frequency (fig. 8). One difference between figures 8 and 9 is that high apparent conductivities occur along a longer part of the Animas River at the intermediate frequency (fig. 9) beginning east of Silverton and continuing to upstream of Eureka. This difference suggests that shallow valley fill sediment is not the sole source of high conductivities. The bedrock is likely more weathered and fractured along the Animas River part of the Silverton caldera structural margins. Another line of evidence that the valley fill is not thick is that the magnetic field map (pl. 3) does not have a pronounced magnetic low along the river basin. A magnetic low would be indicative of thick nonmagnetic sediment.

The CSR map for the lowest frequency is given in figure 10. The apparent conductivity for this frequency is 10 times lower than that for the intermediate frequency shown in figure 9. Apparent conductivity anomalies in this map are smoother than the next higher frequency because again there is greater averaging of the signature of subsurface electrical features. The depth of penetration at the lowest frequency is on the order of 40–50 m. Again there is greater correlation of high apparent conductivities along the upper Animas River drainage than other drainages in the study area. This is likely due to alteration of bedrock along the caldera ring fractures that form the southeastern margin of the Silverton caldera. It is interesting that this is the only part of the caldera structure that has an electrical signature. This suggests that clay minerals are not a large part of the altered rocks along other areas of the caldera margin.

Apparent Conductivity Features

Conductivity anomaly 1 (fig. 11) is an apparent conductivity high with a low at the center. The apparent conductivity high is one of the highest in the survey. The anomaly is prominent in the mid and low frequencies (figs. 9 and 10), suggesting that the surface expression may not be obvious. The general shape is suggestive of an alteration halo around a buried intrusive. The high conductivity (red colors) is situated in an area of moderately high (yellows) apparent conductivity located to the north of linear feature A. This linear feature trends northwest to southeast and correlates well with a fault zone shown by Yager and Bove (2002; Yager and Bove, this volume, pl. 1). In one interpretation of this setting, a silicified fault zone is present that has acted as a barrier to hydrothermal waters. The impounded hydrothermal waters could have caused alteration to the northeast of the structure (D.J. Bove, oral commun., 2002). A high apparent conductivity is correlated with this alteration. This structural zone may also control modern ground-water flow (Wright, Kimball, and Runkel, this volume, Chapter E23).

Linear feature B has a similar trend to linear feature A and passes through the area of the May Day mine (MA, fig. 11). The feature is present on the intermediate- and low-frequency apparent conductivity maps (figs. 9 and 10). That these trends are not as clear on the high-frequency map suggests that the surface expression may not be obvious. This may be why surface geologic maps (Yager and Bove, 2002; Yager and Bove, this volume, pl. 1) do not indicate a prominent structure in this area. Smith and others (2001) suggested that linear feature B may be a fracture system that could control the ground-water flow. Local surficial ground-water flow interaction with the May Day mine dump is also documented (Smith and others, 2001; Wright, Kimball, and Runkel, this volume). Thus this area may be a good example of both surface (mine waste) and subsurface (fracture controlled) ground-water paths. Linear features C and D may indicate similar structures extending to the northwest from linear feature B. These trends are also not as clear on the high-frequency apparent conductivity map (fig. 8).

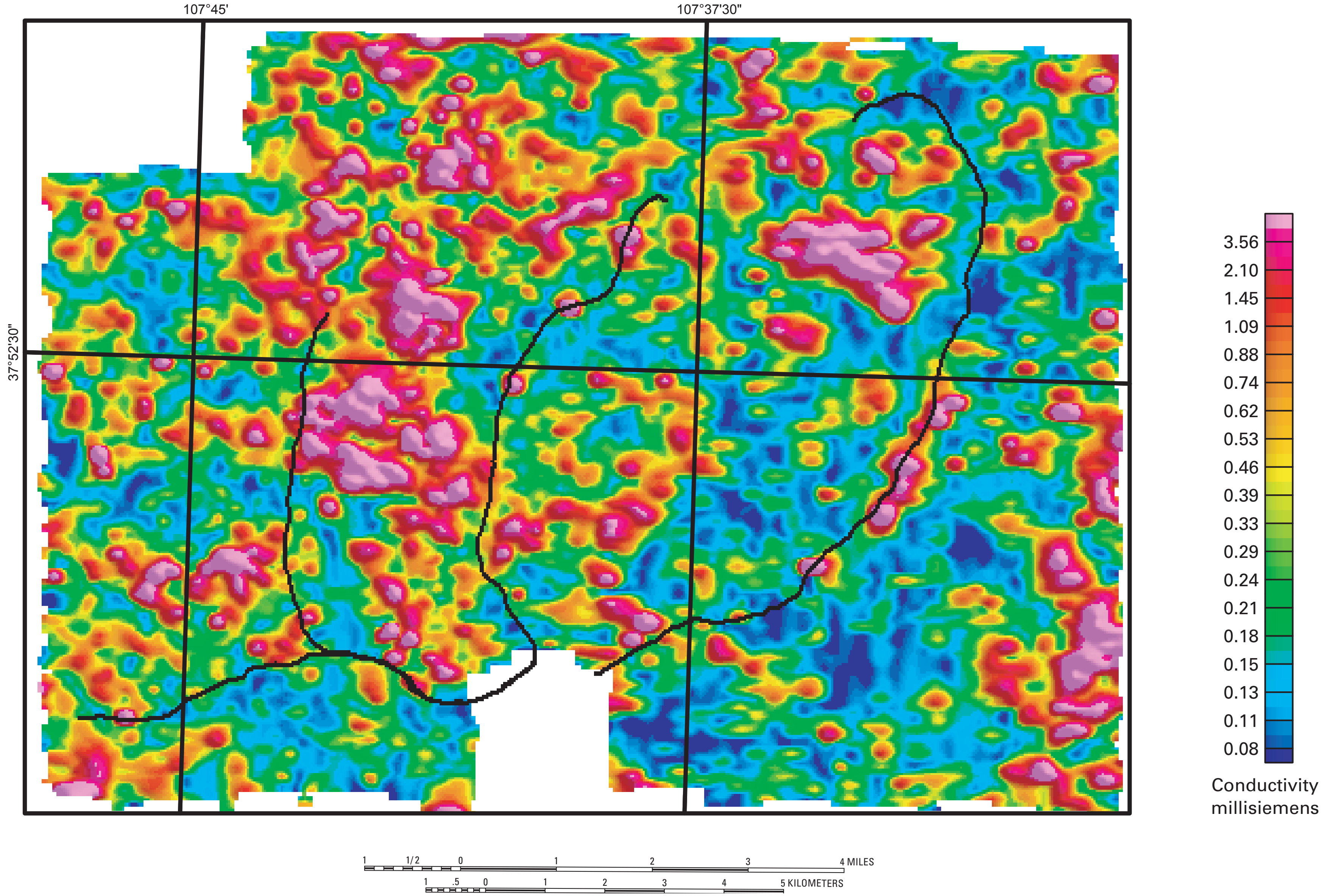


Figure 8. Color shaded-relief apparent conductivity map at 36,930 Hz of Animas River watershed study area. Sun direction is from northeast. Black line, flightline flown along selected drainage as shown in figure 3. Figure is of same area as shown in the 1:48,000 apparent conductivity map (pl. 4).

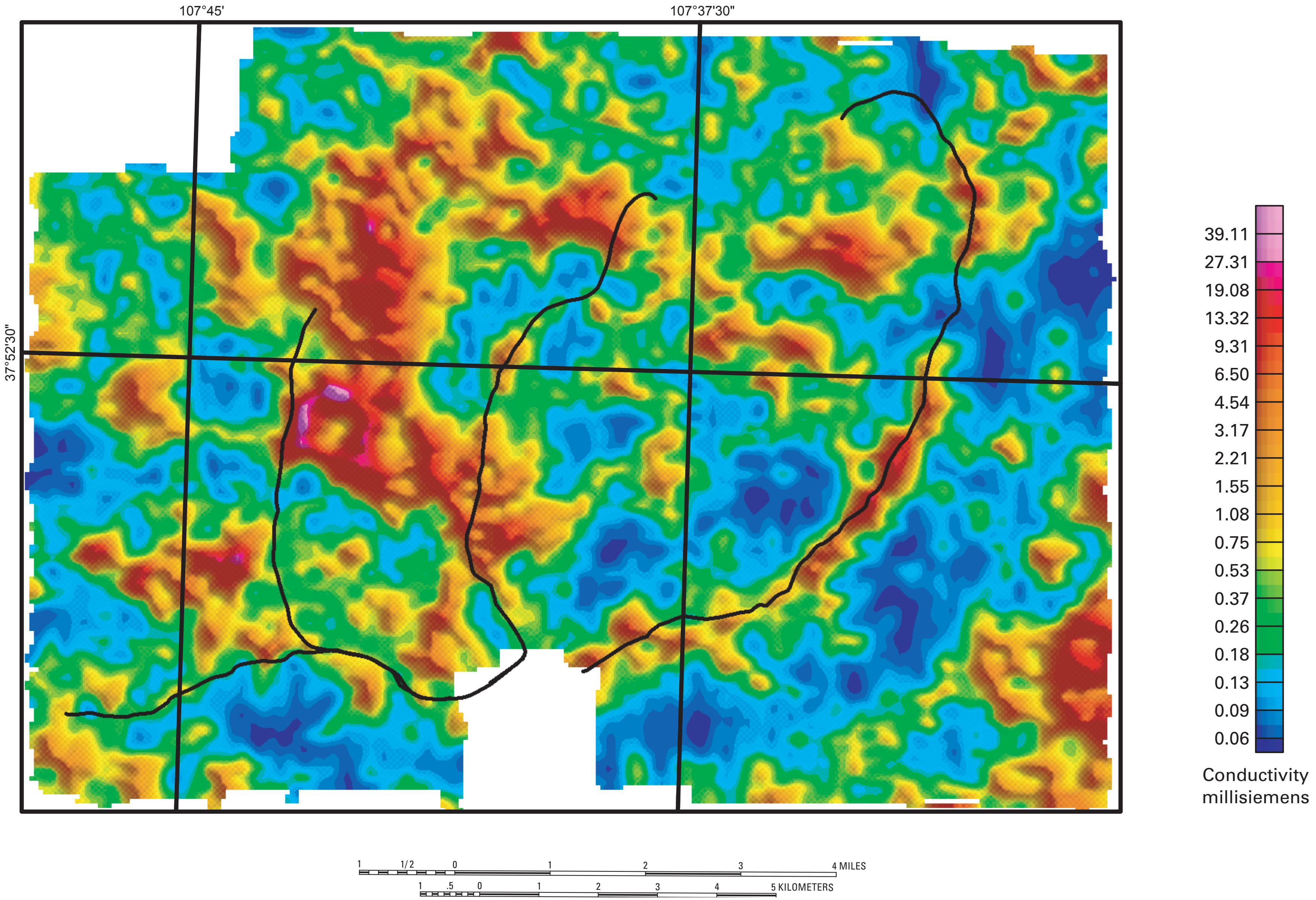


Figure 9. Color shaded-relief apparent conductivity map at 4,310 Hz of Animas River watershed study area. Black line, flightline flown along selected drainage as shown in figure 3. Figure is of same area as shown in the 1:48,000 apparent conductivity map (pl. 4).

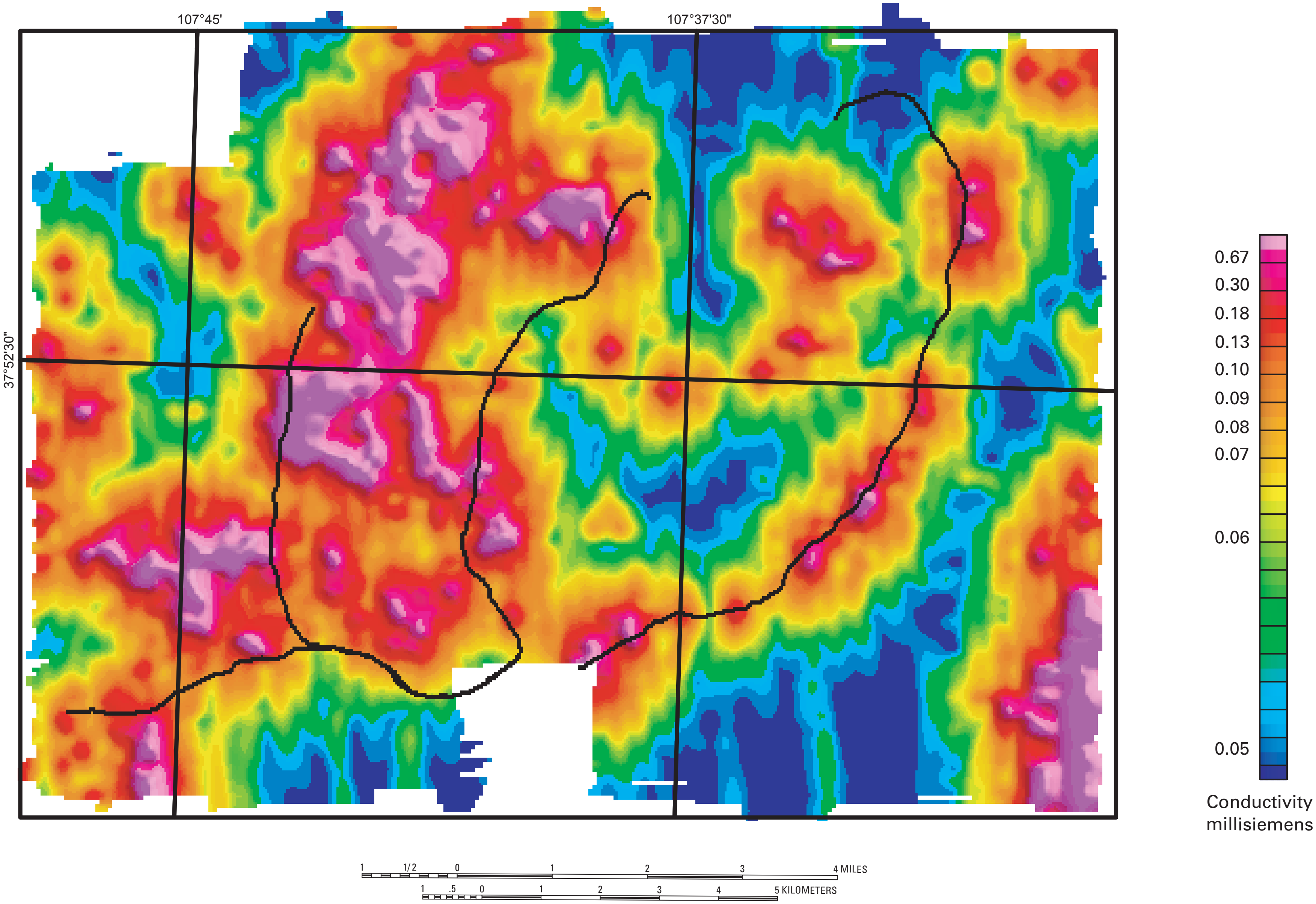


Figure 10. Color shaded-relief apparent conductivity map at 935 Hz of Animas River watershed study area. Black line, flightline flown along selected drainage as shown in figure 3. Figure is of same area as shown in the 1:48,000 apparent conductivity map (pl. 4).

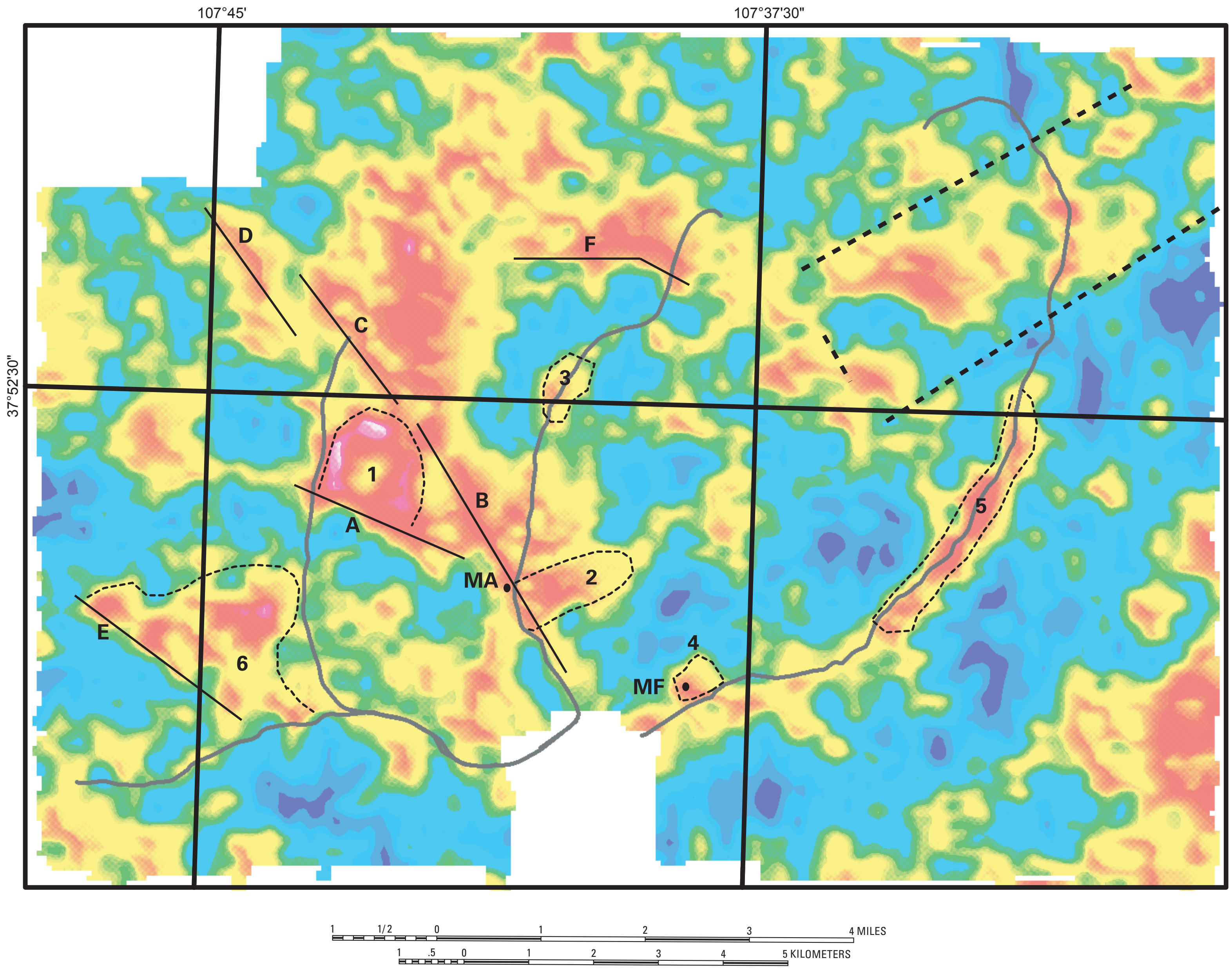


Figure 11. Apparent conductivity map showing selected anomalous features. Curving solid gray line, flightline flown along selected drainage as shown in figure 3. Figure is same area as shown in the 1:48,000 apparent conductivity map with the same color scale (pl. 4). Letters identify linear features (straight black lines); MA, May Day mine; MF; Mayflower tailings. Numbers indicate high conductivity anomalies.

High apparent conductivities located in the area labeled 2 in fig. 11 correlate with a mapped landslide (Yager and Bove, 2002; Yager and Bove, this volume, pl. 1). The high apparent conductivity is present at all frequencies, which suggests that the source extends from surface to depth. Clay minerals, associated with alteration of the Silverton Volcanics, are likely the source of the anomalous conductivity. The clay-rich lithology is favorable for the development of landslides and may also control local ground-water flow.

Anomaly 3, located along Cement Creek, is in the area where an iron-rich bog described in several other studies (Wirt and others, this volume; Kimball and others, this volume; Stanton, Yager, and others, this volume, Chapter E14) has formed. This high conductivity anomaly has an expression at the lower frequency and a very limited expression at the highest frequency. One hypothesis concerning the genesis of the bog is that it could be located on a fracture system that is acting to focus the flow of ground water. The electrical signature is not suggestive of a linear fracture system. In addition, ground electrical geophysical surveys on the bog surface do not indicate any depth extent to the high dissolved solids observed at the surface. The localized conductivity high is due to downcutting of the valley in this part of Cement Creek that has forced ground water to the surface (Vincent and others, this volume, Chapter E16).

Linear feature F (fig. 11), located at the head of Cement Creek, is defined as a boundary between low and high apparent conductivities. The general trend of linear feature F correlates with the Bonita fault and the western part of the Sunnyside fault (Yager and Bove, 2002; Yager and Bove, this volume, pl. 1). The specific location of this linear feature may indicate a part of the fault system that is important in controlling local ground-water flow.

High conductivity anomaly 4 (fig. 11) along the Animas River is located at the Mayflower Mill mine-waste piles (MF) and adjacent flood plain along the river. Ground geophysical surveys in the flood plain along this part of the drainage in 2001 showed localized shallow-subsurface very high conductivity between the waste piles and the Animas River. This high conductivity was correlated with sulfide tailings that were removed in 2003 by Sunnyside Gold, Inc. The high conductivity anomaly, in general, is likely to have resulted from the high dissolved solids in ground water and the presence of conductive sediment in tailings. There is also a large fault zone exposed in the bank of the Animas River that may be the source of some of the high conductivity on the south side of the river east of anomaly 4.

High conductivities are associated with much of the Animas River northeast of Silverton. Conductive anomaly 5 is present on all frequencies (figs. 8, 9, and 10). The source of high conductivities is likely both valley fill and altered bedrock along the valley. The extension of the conductive features to depth could be an indication of structures bounding this part of the Silverton caldera. As a point of interest, note that other major drainages (Mineral Creek, South Fork Mineral Creek, Cement Creek) do not have as extensive areas of high conductivity, even though there is fill along their valleys. The implication is that the ring fault structure is more developed and altered with depth along the Animas River drainage than in the other drainages. Thus both surficial and fracture-controlled ground-water flow is particularly important along this drainage.

Conductivity anomaly 6 and linear feature E (fig. 11) are correlated with the mineralized system at peak 3,792 m (Yager and Bove, this volume; Bove and others, this volume). The high conductivity anomaly is correlated in general with mapped quartz-sericite-pyrite lithology. No single mapped structural feature correlates with linear feature E southwest of this mineralized system (fig. 11).

Hydrologic Implications

Variations in electrical conductivity can be generalized for different types of ground-water systems for the Animas River watershed study area. Water-bearing units in the study area can be conceptually grouped as (1) near surface, (2) weathered surficial bedrock, and (3) deeper bedrock. Ground-water flow within water-bearing units can be associated with and influenced by lithologic and structural heterogeneities that can have contrasting physical properties (electrical conductivity and magnetization). These contrasts in physical properties are shown by the heterogeneous responses in the airborne geophysical maps. Predicting subsurface ground-water flow is important in understanding the transport of contaminants from historical mine sites.

Ground-water flow exists in the Holocene and Pleistocene deposits of clay to boulder-size sediments that are mapped as alluvium, alluvial fans, talus slopes, colluvium, landslides, glacial deposits, and bog deposits (Blair and others, 2002; Yager and Bove, 2002; Yager and Bove, this volume). Areas of silt-size sediment may contain clay minerals that cause a high electrical conductivity. These areas may be associated with alluvium, colluvium, and landslides. Alluvial valley fill may also contain organics (peat type deposits) that can increase the electrical conductivity. Talus slopes and gravel deposits without either clay or water containing high dissolved solids will have low electrical conductivity or be resistive. Rock glaciers that consist of ice cores with sand and boulders are likely to be areas of very high electrical resistivity (very low conductivity). The magnetization of most of the surficial deposits is low except where sediment was derived in place from magnetic bedrock.

The Silverton Volcanics of the Animas River watershed study area are described by Yager and Bove (this volume) as consisting of a basal unit (Burns Member), an overlying (but locally interfingering) pyroxene andesite member, and the Henson Member. The older Burns Member of altered lavas and tuffs has the highest silica content and occupies the central part of the Silverton caldera. The corresponding magnetic low and moderated apparent conductivities are consistent with this lithology, although NRM and hydrothermal alteration may play a role in causing the low magnetic anomalies. The youngest Henson Member consists of interfingering volcaniclastics that are marked by relatively high magnetic anomalies and low conductivities (high resistivity). Magnetic highs at the south side of the Silverton caldera and just north of the Animas River are correlated with the topographic highs (ridge crests) that are mapped as Henson Member (Lipman and others, 1973).

As noted in the discussion of the apparent resistivities at different frequencies, a progression occurs from higher conductivities at the highest frequency (shallowest penetration) to lower conductivity at the lower frequencies (greatest penetration). Near-surface crystalline bedrock has permeability attributed to a three-dimensional volume of intense fracturing (Hurr and Richards, 1974; Caine and Tomusiak, 2003). Conceptually for the study area, in this zone of weathered and intensely fractured bedrock, seasonal fluctuations of recharge and discharge take place (Caine, 2003). High electrical conductivities may be developed if the ground water contains high dissolved solids characteristic of many contaminants. Weathering processes may also lead to the development of secondary minerals, in particular clay or zeolite minerals. Both of these conditions will contribute to near-surface high conductivities underlain by low conductivity bedrock. An electromagnetic anomalous signature of this setting would be high conductivities at high frequencies and lower conductivities at the deeper penetrating lower frequencies (fig. 10). A contributing factor to the decreasing conductivity with depth is, conceptually, the decreasing fracturing with depth. As lithostatic pressures increase, open fractures should decrease.

Porosity and permeability of volcanic rocks can be associated with primary depositional features and fractures developed at various scales. Bedrock ground-water flow may exist in highly permeable volcanic rock such as tuffs and breccias. There have been no systematic laboratory or borehole measurements of porosity and permeability of the volcanic rocks in the study area. Huntley (1979) and Caine (2003) have suggested that the San Juan Mountains in general have high permeability due to both fracturing and their lithology (tuffs and breccias, for example). Primary deposition features are the extensive lahars, volcaniclastic deposits, and interbedding between flows. The electrical conductivity of porous and permeable sediments is directly controlled by the conductivity of the pore fluid (Olhoeft, 1985). Consequently, large areas (tens of meters) containing fluids with high total dissolved solids can produce high conductivity signatures in the HEM data.

Caine and others (1996) described a conceptual model of the controls of ground-water flow by faults and fault zones. Faults and fractures within aquifers and water-bearing rocks can act as both conduits and barriers to water flow (Caine and others, 1996). Robinson (1978) and Caine and Tomusiak (2003) have given good descriptions of the hydrologic setting of crystalline rock in terms of the importance of faults and fractures. On the scale of geologic time, fault zones and fractures have certainly served as conduits that have focused hydrothermal fluids to form mineral deposits (Casadevall and Ohmoto, 1977). The same hydrothermal processes that have developed and concentrated mineralization also developed extensive siliceous vein systems that have essentially annealed or plugged the fracture system that existed at the time. Massive siliceous vein systems are likely to have low electrical conductivity (be resistive) (Olhoeft, 1985). Unless these are fractured, they are likely barriers to ground-water flow. In contrast, high conductivity may be due to development of clay in tabular alteration zones along faults that act as conduits.

Evidence for specific ground-water flow paths in the watershed is limited and is summarized as follows. The geophysical features extending from the May Day mine toward Ohio Peak (figs. 7 and 11) suggest a structure that influences ground-water flow over a broad scale (Smith and others, 2001). Arcuate magnetic and conductive features that predominantly follow the Animas River suggest that the ring fracture system (Yager and Bove, this volume) influences ground-water flow. Wirt and others (this volume) suggest that development of bogs or precipitates near Fairview and Placer Gulches (middle part of Cement Creek, pls. 3 and 4) is partly due to fracture system-controlled springs. Neither area is near identified linear geophysical anomalies, but both are near anomalous electrical conductivity lows in the intermediate and low electromagnetic frequencies (figs. 9 and 10). The high conductivity anomaly near the Mayflower mine-waste piles is in part associated with a localized flow path that transported high metals from a sulfide-rich mine waste that has been removed. Thus in general the airborne geophysical surveys can be used in the study of both large- and small-scale ground-water flow paths.

Conclusions

The airborne electromagnetic and magnetic maps for the Animas River watershed study area contain features that selectively emphasize specific lithology and structure and offer clues in understanding the ground-water flow regime. The lithology of the caldera fill is associated with magnetic lows and conductivity highs. Younger intrusives ringing the caldera have distinctive geophysical anomalies reflecting differing lithologies.

The geologic maps of the study area show numerous structures, but only a few of these are associated with identified geophysical anomalies. Conversely, data on the geophysical maps suggest structures that have not been previously mapped. Geophysical maps identify areas of near-surface and subsurface electrical and magnetic physical property contrasts that suggest structural features. These structures possibly influence ground-water flow.

Electrical and magnetic signatures can be associated with particular lithologies. Only qualitative relationships have been suggested here. McDougal and others (this volume) have used predictive models to quantitatively relate geophysical signatures to acid-neutralizing terrains and terrains favorable for the occurrence of veins and structures. Physical property differences between Tertiary intrusives enable them to be classified on the basis of their geophysical signature. Low conductivity and magnetic intrusives may have more restricted ground-water flow than those that have been altered producing magnetic lows and a conductive signature.

Near-surface high conductivity anomalies associated with some mine-waste piles may indicate ground water containing high dissolved solids or a source of metal loading to the ground water. Other areas of intense hydrothermal alteration may be a surface source for ground water containing high dissolved solids.

The geophysical data have been used to identify areas possibly influencing surface and bedrock ground-water flow. Location of subsurface ground-water flow paths is a critical part of abandoned mine land studies.

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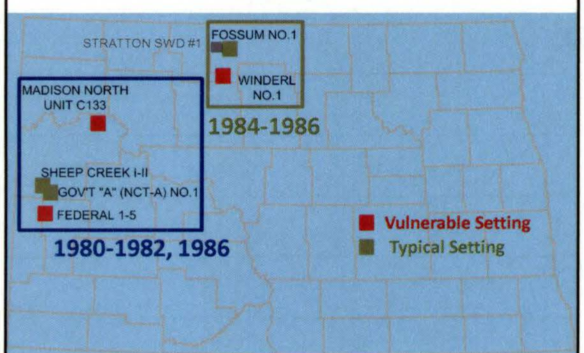
Reserve Pit and Brine Pond Studies in North Dakota

Presented to the
Energy Development and Transmission Committee
Senator Rich Wardner, Chair
Minot, ND
April 8, 2014

Ed Murphy
North Dakota Department of Mineral Resources
Geological Survey

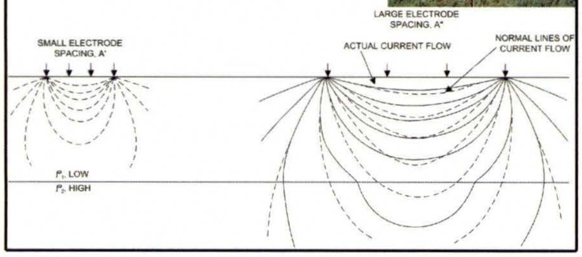
RESERVE PIT & BRINE POND STUDIES



NORTH DAKOTA GEOLOGICAL SURVEY

- **1980 - 1982** Studied **four buried reserve pits** in western North Dakota (one report, one paper, numerous presentations). **1986** Resampled **Apache site** (one report, one presentation).
- **1984 - 1986** Studied **two buried reserve pits** in north-central North Dakota (one report, several presentations).
- **1984 - 1985** Studied an **abandoned brine holding pond** in north-central North Dakota (two reports).

EARTH RESISTIVITY SURVEY



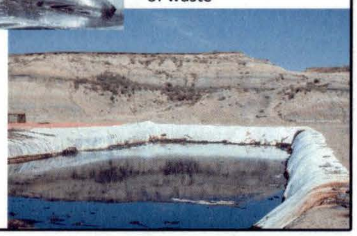
MONITORING WELL (PIEZOMETER) INSTALLATION

LYSIMETER (soil water sampler) INSTALLATION

Reserve/Mud Pits

Dimensions:
150 feet x 60 feet
10 feet deep

30,000 - 50,000 cubic feet of waste

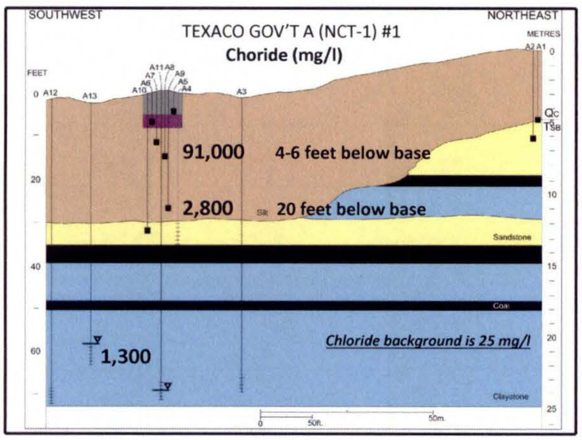


1980

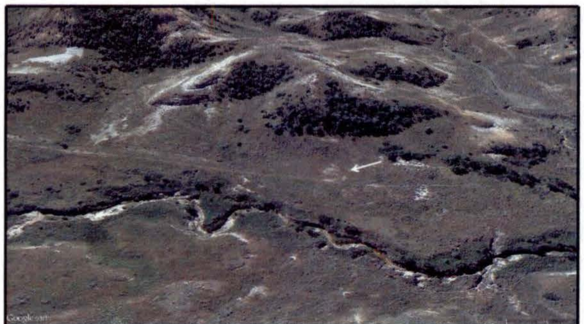
TEXACO GOV'T A (NCT-1) #1 drilled in 1960
BELCO PETROLEUM SHEEP CREEK BN 1-11 drilled in 1977

GOV'T A (NCT-1) #1 drilled in 1960

TEXACO GOV'T A (NCT-1) #1

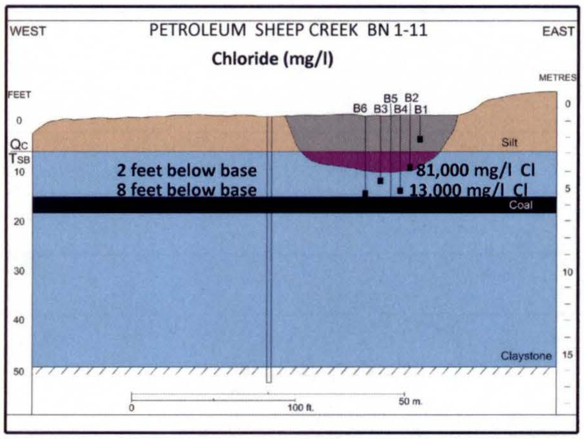


BELCO PETROLEUM SHEEP CREEK BN 1-11 drilled in 1977



2011

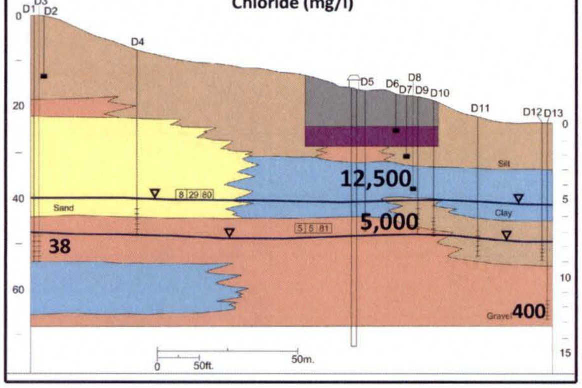
BELCO PETROLEUM SHEEP CREEK BN 1-11

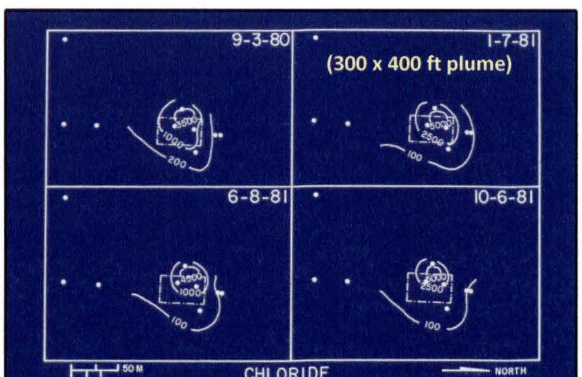


TEXACO CHARLSON MADISON NORTH UNIT C133 drilled in 1955

Produced oil 1955-1966.
No brine pond in 1959 aerial photograph.
Saltwater injection well 1966 – 1982.
Plugged and abandoned in 1984.

TEXACO CHARLSON MADISON NORTH UNIT #C133
Chloride (mg/l)





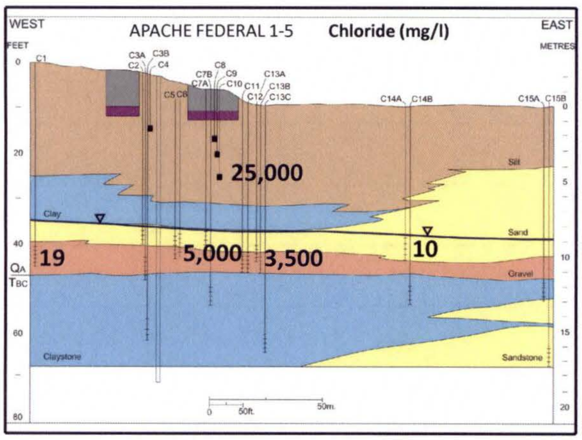
TEXACO CHARLSON MADISON NORTH UNIT #C133

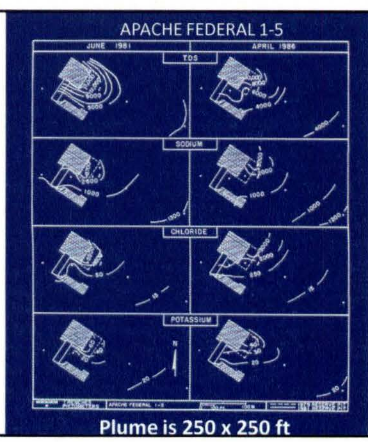
APACHE FEDERAL 1-5 drilled in 1979

APACHE FEDERAL 1-5 deepened in 1981

Apache Federal 1-5
Produced oil from 1981 – 1984.
Plugged and abandoned in 1984.

APACHE FEDERAL 1-5
Installing monitoring wells in 1981.





RESERVE PIT STUDY
WESTERN NORTH DAKOTA

- Leachate is being generated from buried drilling fluid at each of the four western ND study sites.
- The amount of leachate reaching the water table is assumed minimized by clay attenuation and evapotranspiration.
- Very little leachate is likely reaching the saturated zone at the two study sites in the Roughrider Field based on the reduction seen in the unsaturated zone.

RESERVE PIT STUDY
WESTERN NORTH DAKOTA

- Leachate at Federal 1-5 covers an area of <u>250 x 250 feet</u>.
  - Chromates detectable in leachate within the unsaturated zone but not in the saturated zone – levels were higher in the saturated zone in 1986.
- Leachate plume in the Texaco Charlson Madison (North) Unit is approximately <u>300 x 400 feet</u> in the upper saturated zone (top 40 feet).
- This study determined that leachate will be generated by the current method of reserve pit reclamation. Therefore, it is important to focus attention in areas where leachate will degrade the groundwater.

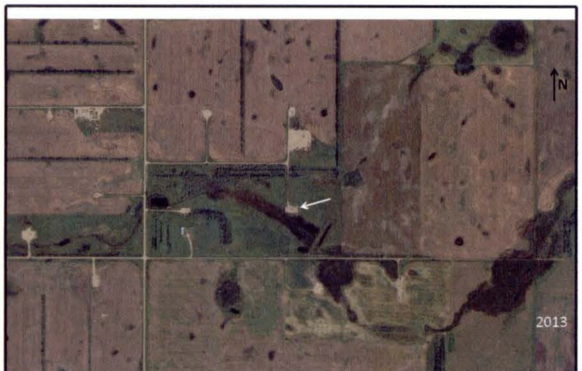
RESERVE PIT STUDY: WESTERN NORTH DAKOTA
1986 CONCLUSIONS

- In general, groundwater chemistries and the extent of the leachate plume relatively unchanged from 1981 to 1986 at Apache Federal 1-5 site.
- Suggested alternative methods for environmentally sensitive sites including closed mud system, solidification, solids control system, central disposal sites – noted central disposal sites must be carefully chosen because the increased volume increases the chances for widespread groundwater contamination.
- There are settings such as the Little Missouri River floodplain, Little Muddy, etc where there should be no burial of waste drilling fluid.

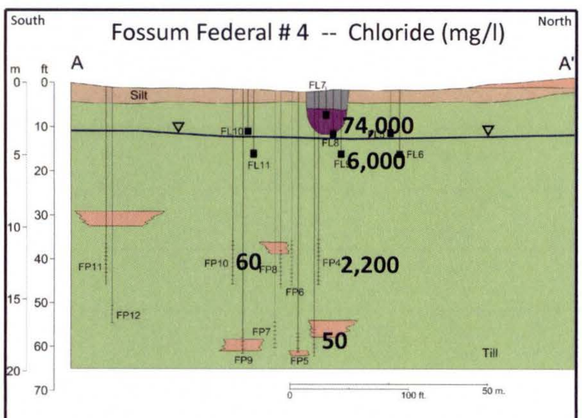
RESERVE PIT STUDY

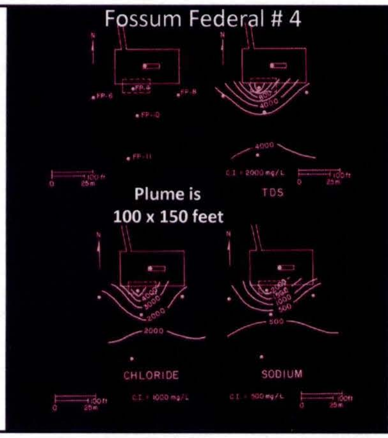
NORTH-CENTRAL N. DAK. 1984

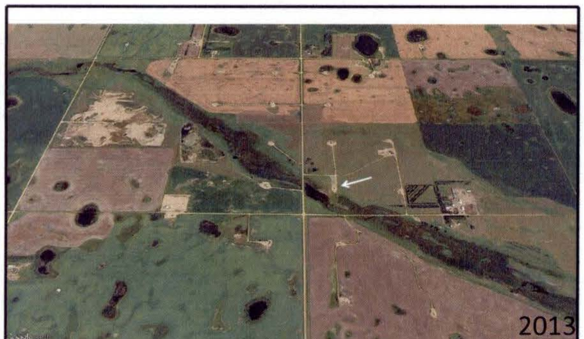
- Two reserve pits studied; one in till (Fossum) the other in sand and gravel (Winderl).
- Installed 45 piezometers and 13 lysimeters, took 700 resistivity readings, obtained 160 water samples for analysis.



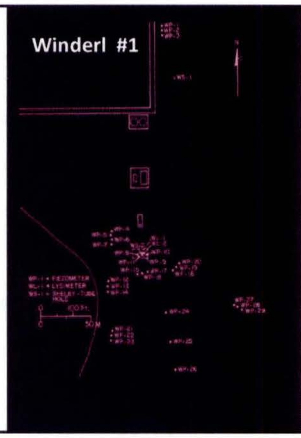
Fossum Federal # 4 drilled in 1978.
Producing oil 1978 – to the present.



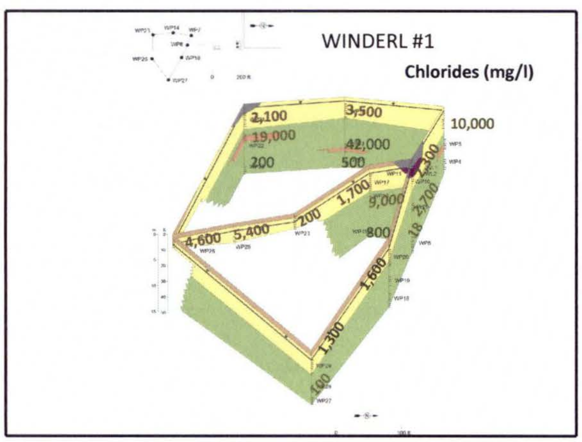


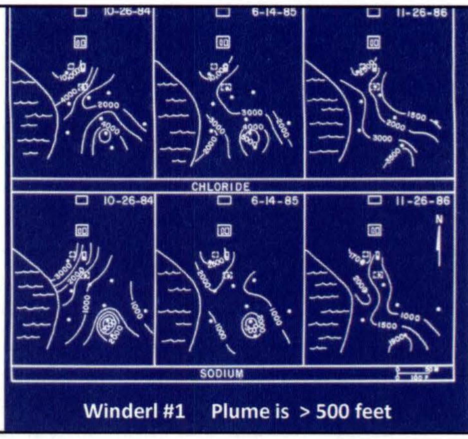


J.J. WINDERL # 1 -- drilled in 1959 and deepened in 1980.
Producing oil 1959 – to the present.




Winderl # 1 looking south



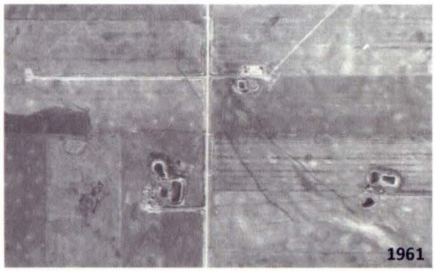


RESERVE PIT STUDY: NORTH-CENTRAL N. DAK.
1985 CONCLUSIONS

- Leachate at Fossum site was detected in an area 100 x 150 feet and to a depth of at least 60 feet around the buried drilling mud.
- Leachate at the Winderl site migrated beyond the 500 foot study area.

Under today's rules, the Winderl (X) and these other two locations (X) would require a closed mud system due to a high watertable and near surface sand and gravel deposits.

BRINE HOLDING PONDS



WILEY FIELD
Madison Pool

CUMULATIVE PRODUCTION (as of 1/1/82)
9,078,035 Barrels of oil
18,063,255 Barrel of salt water

Total Dissolved Solids (TDS) of brines in the Wylie Field range from 19,000 to 250,000 mg/l (seawater 30,000 – 50,000).

BRINE HOLDING PONDS

Operated in North Dakota from 1951-1982.

NDGS personnel began field investigating and condemning brine holding ponds in the 1960s.

The exact number of brine ponds that existed from 1951-1982 is unknown (*est. 2,000 – 3,000*).

BRINE HOLDING PONDS

Dimensions:

45 x 60 ft up to 90 x 180 ft

4 to 9 feet deep

1) Unlined
2) Clay liner
3) Polyethylene liner

WYLIE FIELD STUDY
1984-1985

NDSU Soil Science Department
NDSU Chemistry and Geology Department
NDSU Land Reclamation Research Center
UND Geology Department
ND Mining and Minerals Resources Research Institute
North Dakota Geological Survey

Doll, Wollenhaupt, Carter, Foss, Richardson, Prunty, Sweeney, Cudworth, Hoag, Kulla, McCarthy, Elless, Steinwand, Keller, Groenewold, Kehew, Beal, and Murphy.

440 page report

STRATTON SWD #1

Drilled in 1959 by Cardinal Petroleum **(Edson Brown #1).** Produced oil from 1959-1970. Converted to a saltwater disposal well by Phillips Petroleum in 1978 **(Stratton SWD #1)**.

The site contained two brine holding ponds from 1959 to at least 1970 (with dimensions of 100 x 90 ft and 60 x 100 ft and 5 feet deep). This well produced 178,000 barrels of saltwater.

WYLIE FIELD STUDY
1984-1985

NDSU Chemistry and Geology Department
NDSU Soil Science Department.

Characterization of Detrimental Effects of Salts and Other Chemical Constituents Carried in Surface and Subsurface Water from Mine and Drilling Fluid Disposal Pits Buried During Oil Development

Studied seven sites, Stratton SWD #1 is their F1 Site.
- 48 shallow Giddings cores (10-15 feet deep).
- 193 saturated paste extract
- 80 XRD analyses.

WYLIE FIELD STUDY
1984-1985

NDSU Land Reclamation Research Center

Eugene Doll, Nyle Wollenhaupt, Frank Carter

Salt Movement in Buried Brine Disposal Pit Areas as Related to Chemical and Physical Properties of the Soil and Geologic Materials and to the Surrounding Landscape

Studied two sites, Stratton SWD # 1 is their Fossum Site 1.

Electromagnetic soil conductivity meter (EM-38):
58 stations, 116 readings.
55 shallow Giddings cores (10-15 feet deep).
630 saturated paste extract analyses.

NDSU estimated 500 tons of NaCl in the top 10 feet of the Stratton Site. This works out to 22 tons per acre for this site.

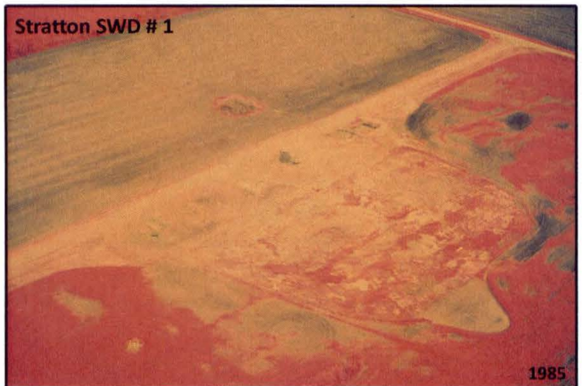
WYLIE FIELD STUDY
1984-1985

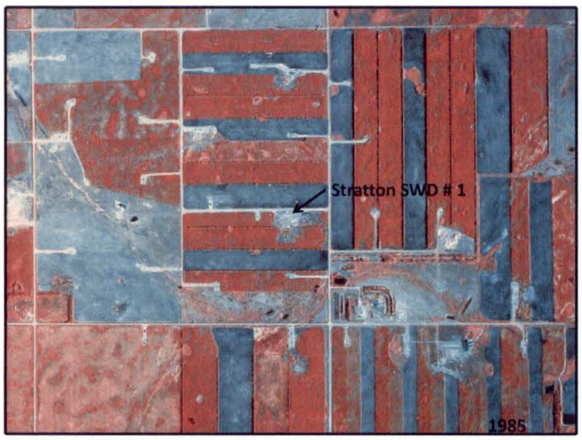
Soil Science Department, NDSU

John Foss, Jimmy Richardson, Lyle Prunty, Mark Sweeney, Doug Cudworth, Brian Hoag

Identification of Salt–Seepage Areas from Oilfield Brine Pits

Analyzed aerial photographs (existing and generated).
Electromagnetic soil conductivity meter (EM-38).



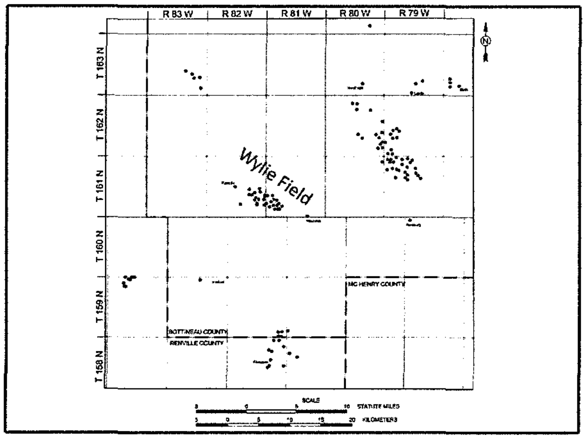


NDSU SOILS DEPT 1984 STUDY

Identified 121 old brine pond sites in Bottineau and Renville Counties.

Estimated the area contaminated by old brine ponds at 1,450 acres (average of 12 acres per site).

Interpreted aerial photographs from various years and scales.



NDSU SOILS DEPT 1984 STUDY
Wylie Field

Studied an area of 15 square miles in Wylie Field and identified 60 old brine pond locations.

Interpreted aerial photographs from various years and scales.

NDSU SOILS DEPT 1984 STUDY
Wylie Field

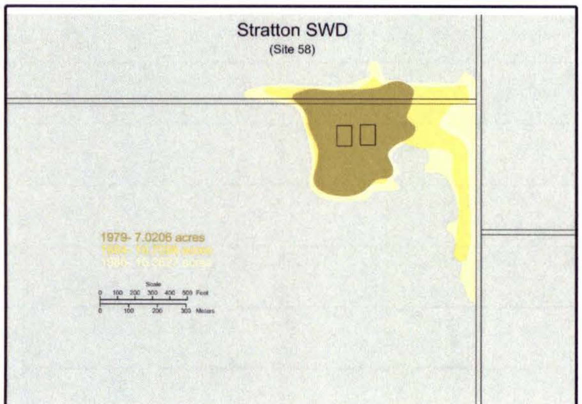
Mapped 23 of the 60 sites.

Salt-impacted area ranged from 0 to 42 acres at each site.

Average impact of 11.5 acres per site.

Total impact of 266 acres.

Electromagnetic soil conductivity meter (EM-38).



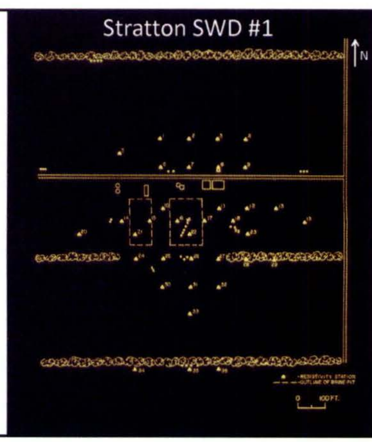
WYLIE FIELD STUDY
1984-1985

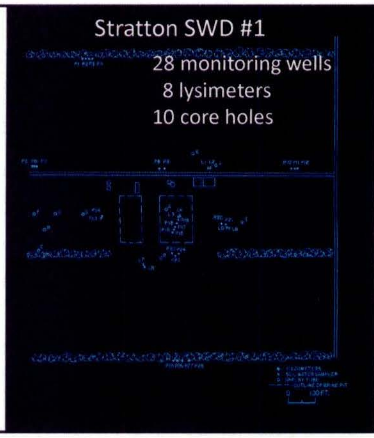
North Dakota Geological Survey
UND Geology Department
ND Mining and Minerals Resources Research Institute

Gerry Groenewold, Alan Kehew, Willie Beal, Ed Murphy

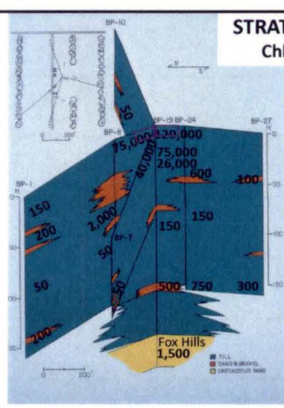
Movement of Leachate From a Buried Oil and Gas Brine-Disposal Pond in the Wylie Field, Bottineau County, ND

Studied only the Stratton SWD #1
- 28 piezometers (down to 220 feet), 8 lysimeters.
- 60 water samples.
- 36 resistivity stations (504 readings).





Installing monitoring wells at the Stratton SWD #1 in 1984.



The site is underlain by 220 feet of till overlying the Fox Hills Formation.

STRATTON SWD #1

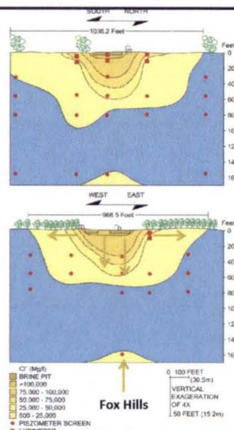
A high salt plume extends laterally around the site over an area of 250,000 ft2 (about 6 acres).

This plume extends to a depth of more than 80 feet (highest concentrations in top 40 feet).

Brine plume restricted to till and not impacting any useable water supply (ND Health Dept concurred in 2006).

Chloride levels at 160 feet (500 - 750 mg/l) appear to be coming from the underlying Fox Hills Formation.

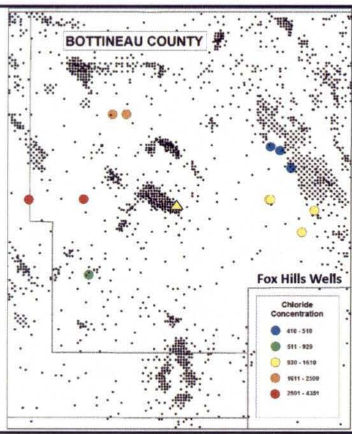
Stratton SWD #1



CHLORIDE LEVELS IN THE FOX HILLS FORMATION

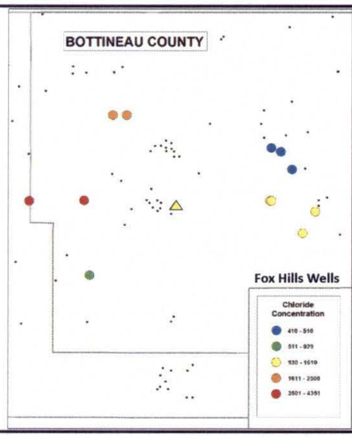
County	Average Chloride Concentration (mg/l)	Number of Water Samples	Number of Wells
Billings	**47**	43	29
McKenzie	**170**	34	NA
Mountrail	**265**	1	1
Williams	**491**	7	4
Ward	**NA**	0	0
Divide	**1220**	7	3
Burke	**NA**	0	0
Renville	**4351**	7	1
West Bottineau	**1514**	11	11
McHenry	**654**	41	24
East Bottineau	**192**	8	8
Rolette	**282**	4	1

Kimberly Fischer, NDSWC, 2014



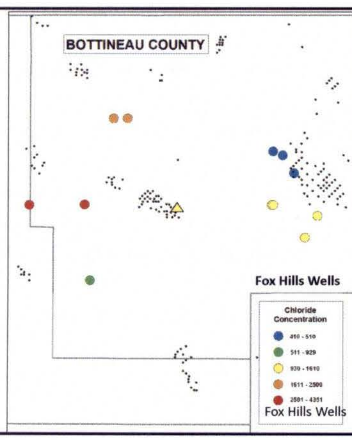
FOX HILLS WELLS
AND
OIL & GAS WELLS

△ Stratton Site



FOX HILLS WELLS
AND
SALTWATER
DISPOSAL WELLS

△ Stratton Site



FOX HILLS WELLS
AND
WATER
INJECTION WELLS

△ Stratton Site

RECOMMENDED REMEDIATION METHODS
1985

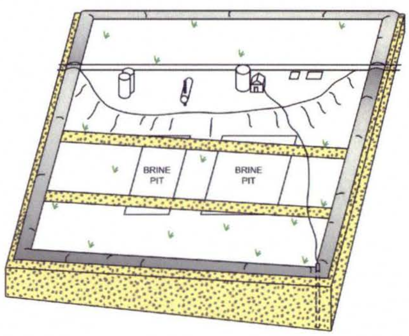
PUMPING WELLS
Hydraulic conductivity of the till is too low to be effective.
Expensive.

IMPERMEABLE MEMBRANE
Would minimize the spread of brine in the unsaturated zone.
Bentonite.
Would not be a long-term solution.

MOUNDING/CAPPING THE SITE
Would reduce the generation of brine leachate from overland flow.
Bentonite and fill.
Would not be a long-term solution.

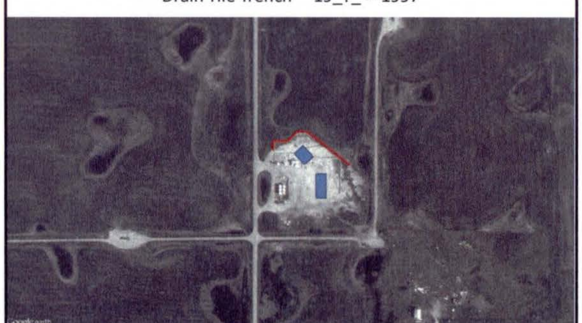
INFILTRATION GALLERY (Gravel-filled ditch)
Would minimize the spread of brine in the unsaturated zone.
Would be a long-term solution.

INFILTRATION GALLERY



1985

Erickson Central Tank Battery, Bottineau County
Drain Tile Trench 19_?_ -- 1997



Drain tile trench approximately 400 ft long, snow fence

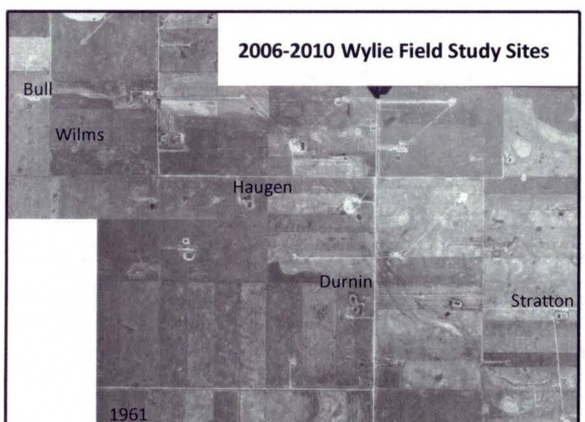
Erickson Central Tank Battery, Bottineau County

General consensus that vegetation recovered in the drain tile area.

ATTEMPTS TO CLEAN UP OLD BRINE PONDS IN THE WYLIE FIELD
2006 – 2010

Sites
Stratton D01 (Stratton SWD #1)
Bull B1R
Wilms A D01
Haugen B1
Durnin A & D01

2006-2010 Wylie Field Study Sites



ATTEMPTS TO CLEAN UP OLD BRINE PONDS
IN THE WYLIE FIELD
2006 – 2010

Soil Parameter Monitoring
Sediment samples from 0-1 feet and 1-2 feet.

Groundwater Monitoring
Durnin Site Three, 15 ft deep monitoring well.
Stratton Site Three, 15 ft deep monitoring well.

Soil Amendment Application
Gypsum, fertilizer, manure, straw application-- lightly tilled.

Water Application
Three times per week at each site due to drought conditions.

Geophysical Survey
Conductivity and resistivity surveys at the Durnin site.

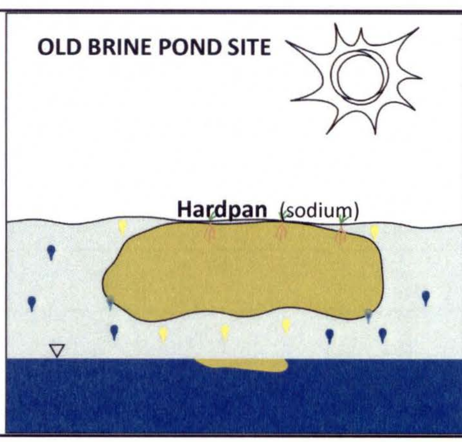
ATTEMPTS TO CLEAN UP OLD BRINE PONDS
IN THE WYLIE FIELD
2006 – 2010 *(50 – 80% reduction)*

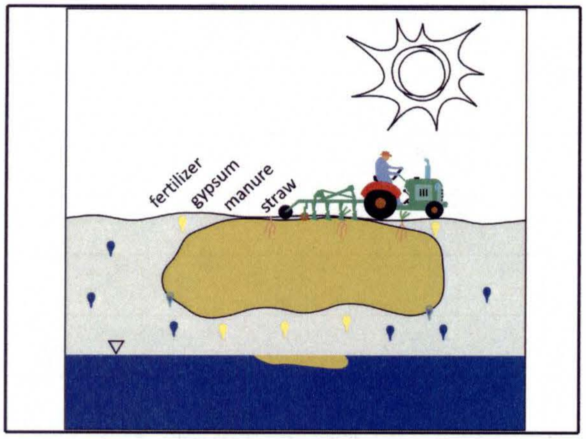
Stratton SWD #1 Site
Chloride levels exhibited a decreasing trend in soils.
Chloride levels did not decrease in groundwater.
Area of surface scaring reduced from 14 acres to 3 acres.

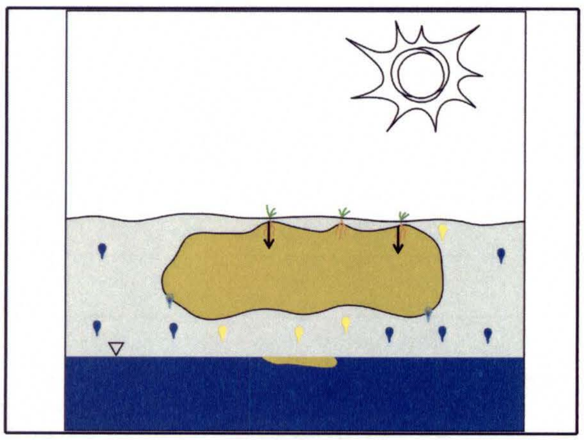
Bull Site
Chloride levels exhibited a decreasing trend in soils.
Area of surface scaring reduced from 3.5 acres to 1 acre.

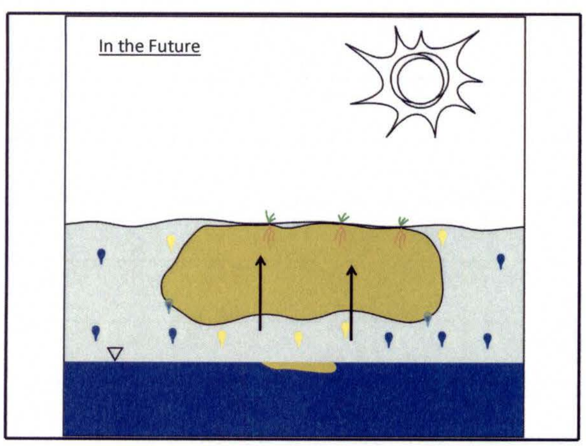
Wilms Site
Chloride levels exhibited a decreasing trend in soils.
Area of surface scaring reduced from 1.5 acres to 0.5 acres.

Haugen Site
Chloride levels exhibited a decreasing trend in soils.
Area of surface scaring reduced from 3.5 acres to 1.75 acres.

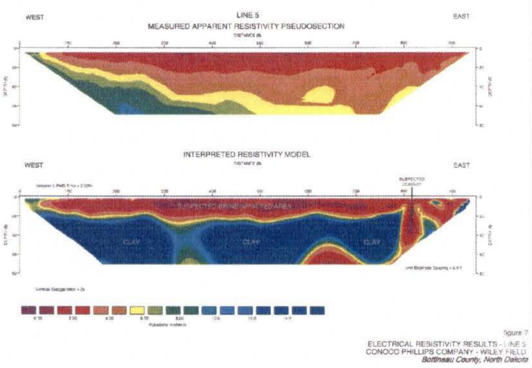



fertilizer
gypsum
manure
straw




In the Future

DURNIN SITE



REJECTED REMEDIATION METHODS
IN THE WYLIE FIELD
2006 – 2010

REMOVE IMPACTED SEDIMENT

Evaluated removing salt impacted sediment across six acres to a depth of four feet (38,000 cubic yards).

Install a 30 mil plastic liner.

Replace with clean fill.

Risky due to likelihood that salt would find its way into the clean fill.

REJECTED REMEDIATION METHODS
IN THE WYLIE FIELD
2006 – 2010

DRAIN TILE SYSTEM

Evaluated installing a drain tile system down to a depth of 20 feet to dewater and flush the system.

Potential for no viable disposal method.

Believe the groundwater impacted area extends beyond site and would continue to migrate into this site into the future.

ADVANCES IN RESISTIVITY

Taken at depth of interest with vertical electrodes.

Surveys now use AC current verses DC current.

Measure actual soil /ground water resistivity vs. "apparent" resistivity.

Bulk soil measurements can be taken around an electrode, in planes between two electrodes.

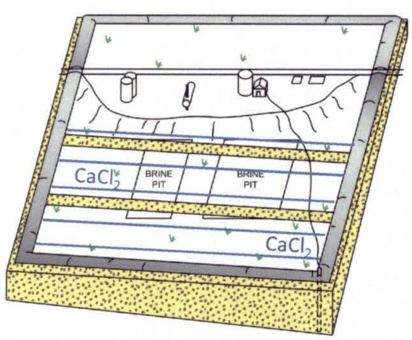
Advances in statistical computer modeling can further increase the resolution of the electric data for 2-D or 3-D display.

Hell Creek Environmental Services

ADVANCES IN DRAIN TILE AND IRRIGATION FLUID CHEMISTRY

Agassiz Drain Tile

INFILTRATION GALLERY



Troy Coons
Northwest Landowners Association
Energy and Natural Resources Committee
Testimony for HB 1401
January 28, 2021

Good morning, Chairman Porter and members of the committee, thank you for taking my testimony into consideration today.

My name is Troy Coons and I am the Chairman of the Northwest Landowners Association. Northwest Landowners Association represents over 560 farmers, ranchers, and property owners in North Dakota. Northwest Landowners Association is a nonprofit organization, and I am not a paid lobbyist.

I am here to testify in support of HB 1401. We appreciate that this legislation ensures additional measures being taken to protect the groundwater; and in turn protecting the health of all citizens and livestock. We have many members who have buried reserve pits on their property, and there is a lot of concern among landowners that these reserve pits will eventually leak. We know that some of them are surrounded by liners, but those liners only have a certain lifetime before they begin to degrade. Many pits do not have liners at all. It seems wise to start thinking of a way to monitor these pits to ensure that they do not contaminate our water or other natural resources when the special waste starts to migrate. We hope to see a continued trend of legislation being put in place to protect the precious resources of North Dakota.

Thank you for taking the time to consider our comments.

Sincerely,

Troy Coons, Chairman
Northwest Landowners Association

Testimony
House Bill 1401
House Energy and Natural Resources Committee
January 28th, 9:00 a.m.
North Dakota Department of Environmental Quality

Good morning Chairman Porter and members of the Energy and Natural Resources Committee. My name is Chuck Hyatt, and I am the Director of the Division of Waste Management of the North Dakota Department of Environmental Quality (DEQ).

I am here today to provide testimony in opposition to House Bill 1401, which amends the Ground Water Protection Degradation Prevention program, North Dakota Century Code Chapter 23.1-11. This program was developed to protect ground water resources, encourage the wise use of agricultural chemicals, and provide public education regarding the preservation of ground water resources. HB 1401 proposes to expand the program by establishing a monitoring program for legacy waste pits and other special waste.

Historic oil and gas exploration left pits on oil well sites used to dispose of oilfield waste including, drilling fluids, cuttings and produced water. As I understand it, these “legacy” waste pits continue to be regulated under the North Dakota Industrial Commission Department of Minerals Resources’ authority.

Special waste is a broad term that includes waste generated through oil and gas exploration and production, waste from mineral, ore, and coal mining operations, and waste generated from energy conversion facilities or power plants, including coal combustion residuals.

House Bill 1401 seeks to establish a new program for the DEQ and others to implement. The DEQ has the following questions and concerns about this proposed program:

First, this bill will modify an existing ground water protection program targeted at agricultural chemicals and includes references specific to agricultural chemical monitoring, such as the role of the NDSU Extension and the Department of Agriculture. Additionally, the bill’s language imposes requirements on the Agriculture Commissioner. It also neglects to acknowledge the Department of Mineral Resources' current efforts to address these legacy issues.

Second, North Dakota has a robust permitting program for special waste disposal facilities. The DEQ's coal combustion residuals special waste program has been in effect since the 1980s. The DEQ is currently seeking primacy to enforce federal coal combustion residuals rules at the state level. Oil and gas special waste landfills have comprehensive design, operations, and groundwater monitoring requirements spelled out in current administrative code. The DEQ has also implemented a groundwater monitoring program, known as our western ambient program, to evaluate shallow aquifers for potential contamination from oil activity. This program samples over 125 wells on a year and a half rotation.

Third, the bill is unclear as to the amount of additional monitoring that would be required. Because of the potential extent of this bill's requirements, we believe it will result in a significant fiscal impact to the DEQ. Understanding how much additional monitoring and the universe of special waste to be evaluated will allow for better quantification of this impact.

Fourth, the term "legacy waste pits" is left undefined. Although it may be understood in the general sense outlined earlier, to clarify legislative intent, a clear definition of what types of features constitute a "legacy waste pit" would be useful and allow for the development of appropriate mitigation activities.

Finally, this bill includes requirements for "other special waste" which is extensively broad and likely duplicative of existing legislation. As mentioned, the DEQ currently has the authority and extensive administrative code language for a permit program that requires groundwater monitoring at permitted special waste landfill facilities.

In conclusion, we ask for clarification in roles and responsibilities and that necessary resources be funded should this bill pass.

This concludes my testimony, and I am happy to answer any questions you may have regarding HB 1401.

COMMISSIONER
DOUG GOEHRING

ndda@nd.gov
www.nd.gov/ndda

NORTH DAKOTA
DEPARTMENT OF AGRICULTURE
STATE CAPITOL
600 E. BOULEVARD AVE. – DEPT. 602
BISMARCK, ND 58505-0020

HB 1401 Testimony
Agriculture Commissioner Doug Goehring
House Energy and Natural Resources Committee
Coteau AB
January 28, 2021

Chairman Porter and members of the committee, I am Agriculture Commissioner Doug Goehring. I'm here today to provide neutral testimony on HB 1401 and to answer any questions the committee would have regarding my responsibilities proposed in this bill.

HB 1401 proposes adding a requirement under chapter 23.1-11-06 of the North Dakota Century Code that mandates the Department of Environmental Quality establish standards for "special waste" and that we would be responsible for implementing mitigation measures to prevent future contamination of ground water from "special waste."

I understand that these "special waste" sites around the state can and sometimes do have an impact on agriculture and why some would want the Agriculture Commissioner to oversee the development and implementation of mitigation measures so that agriculture is adequately represented. I also serve on the North Dakota Industrial Commission and have oil and gas under my portfolio as well so I guess it makes sense to add me as most "special waste" being generated in the state is a product of oil and gas production. If the legislature sees fit to assign me with this task, I would be happy to work with DEQ on its development and implementation.

However, I do have some concerns I would like to point out to the committee for consideration. I believe the Department of Environmental Quality currently monitors "special waste" pits and already has authority over mitigation of these sites. As I stated we would be happy to work with DEQ on development of future mitigation measures to ensure agriculture is represented, but we would have to rely heavily on their expertise for its creation as I do not have anyone in my Department that has specific knowledge of "special waste".

Chapter 23.1-11-06 lays out the requirements for DEQ's ground water quality monitoring program. While they may monitor for pesticides, this is their program and is separate from our pesticide water quality program. They are solely responsible for implementation of this program and are not even required to share their results with us. Under this section they are also the entity required to implement mitigation activities or remedial action and I'm only referenced in this statute to allow authority to implement rules pursuant to chapter 4.1-33 of our pesticide law if necessary, to prevent future contamination of groundwater. The language as currently written in HB 1401 essentially would require me to develop mandatory requirements for another agencies program that we have no affiliation with. There may be cleaner ways to achieve the same goal intentioned in this bill than the way it is currently written.

Chairman Porter and members of the committee, I'm willing to assist in whatever manner you deem necessary, and I only ask that you take my concerns into consideration when deliberating this proposed legislation. Thank you for the opportunity to comment on this bill. I'd be happy to answer any questions you may have.

findooley@gmail.com

To:	Todd Porter; Dick Anderson; Glenn Bosch; Bill Devlin; Pat D. Heinert; George Keiser; Mike Lefor; Andrew Marschall; Shannon Roers Jones; Matthew Ruby; Denton Zubke; Ron Guggisberg; Zachary Ista; Chuck Damschen
Cc:	Fintan Dooley; dglatt@nd.gov; Marvin Nelson; Donald Nelson; Paul Neilan
Subject:	Re: Salt Contaminated Land and Water Council's support of a Special Monitoring Measure, House Bill No. 1401
Attachments:	2020-1-22 Delzer - Burgum Alliance.pdf; 2020-11-23 Reinvest in North Dakota.pdf; 2021-1-4 Historic Produced Water Spill Site Characterization by Kerry Sublette.pdf; 2020-5-5 PowerPoint for Presentation.pdf; 2021-1-23 BIG4 Acres.pdf

Dear Chairman Porter and Committee Members,

Just an hour ago, I learned about yet another hearing to consider tomorrow morning at 8:00 am on January 29, 2021 whether to approve or not House Bill No. 1401. The Salt Contaminated Land and Water Council (SCLWC), a 501(c)(3), North Dakota Educational Non-Profit, has the following comments in the form of this email and its attachments on House Bill 1401.

I understand Rep. Marvin Nelson's bill is being referred to as a **"Special Monitoring Measure."** I understand that Rep. Keiser has asked, "Is this really a problem" and he received an uncertain response from David Glatt. The visual evidence that North Dakota has a major problem is available on pages 2 and 3 of the first attachment and actually measured acre by acre in the fifth attachment. Online pictures are available at www.nddeadlands.org and www.oilindustrydeadlands.org. Online soil science papers are available at www.saltedlands.org.

On behalf of the SCLWC, I respectfully remind David Glatt that he has spoken more candidly about salt spills in the past, when he declared, "We cannot let happen in the Bakken what has happened in Bottineau County." What is happening in the Bakken and Bottineau County is decades of salt spills which continue in Bottineau County and more recently, if you consider 2009 recent an endless series of salt spills. Respectfully now without blaming anyone we haven't found them all. As Mr. Helms said to me two Sundays ago, "We have 20,000 sites (to monitor). The coal industry has seven (mines to monitor)."

Your approval of this bill will signal a new beginning and honesty that is overdue because our State inspectors are underfunded and over taxed, if they are going to protect private property from oil industry spills. As is implied by Director Helms, the 20,000 sites and on your honor spill reporting system we use has left us in an awkward position. Here is the hope. We can now locate spill sites using satellite technology, planes, and drones and by ground truthing farmers can be trained to find the limits of the spill sites using new and affordable technology.

One retired State Official tells us the problem is massive. The State has since 1951 taken private property in each instance in which a spill occurred and the State did not require a clean-up. Steve Tillitson tells how. He long served as the North Dakota Health Department Solid Waste Management Director, made this expression to veteran reclamation manager, Lance Loken. Mr. Tillitson confirmed the same warning in a conversation with me:

Each unreclaimed salt water disposal site is an unpermitted solid waste disposal site.

The State has not monitored special waste, salt water and has not and has not done its duty either under the statutes and rules or under the constitutional duties imposed by the Public Trust Doctrine. I request an opportunity to explain but for now let me identify my attachments.

The first attachment is an invitation to Representative Delzer to assist Governor Burgum in a fresh start on the States Legacy of Salted Lands and Oil Industry Junk Yards. $2 million would allow an honest assessment of the acreage involved. We can find all the Dead and Dying Lands associated with uneconomic oil wells and abandoned ***oil industry junkyards.*** See aerial photos them in the gallery at www.oilindustrydeadlands.org or www.nddeadlands.org. One further thought, we can use satellite, planes and drones to find and estimate the size and likely cost of reclaiming acres taken by the State's default. More on this available at www.saltedlands.org.

The second, third and fourth attachments tell the many reasons for hope that with modern technology and breakthroughs in soil science reclamation of salt damaged lands has never been more affordable. See especially the fifth attachment which was prepared by a most capable young agronomist, Cody Hatzenbuhler, who is cooperating with a team of senior soil scientists headed by Kerry Sublette. Steve Apfelbaum, one of the nation's most forward thinking restoration botanists has informed the Governor that Wall Street wants to invest $1 billion in restoring the productivity of our State's Dead and Dying Lands if only State's Public Trustees matches Wall Street's investment. Yes, bonding again!

It is a stark choice: Undertake a new beginning by monitoring and regulating special waste. Kicking the can down the road will trigger decades of litigation, in which the State stands in the dock, perhaps actually alone. Why? Because the State stands in the shoes of the dead and the walk-offs of the oil industry. Few, if any, in the 67 Legislative Assembly are willing to change corporate immunity and impose lability on even the most contemptuous oil industry executives, not even in the $1 million dollar clean up circumstance which so offended DMR Director Lynn Helms.

Please allow me to testify in person and answer questions about the way forward without wasteful, time consuming and embittering litigation. I request that this email and its attachments be accepted into the committees record of testimony on House Bill No. 1401. If my request cannot be allowed, please tell me. I will try again following whatever suggestions you may give me. I prefer to testify in person tomorrow morning.

Respectfully submitted by SCLWC – Lobbyist No. 384.

Fintan L. Dooley

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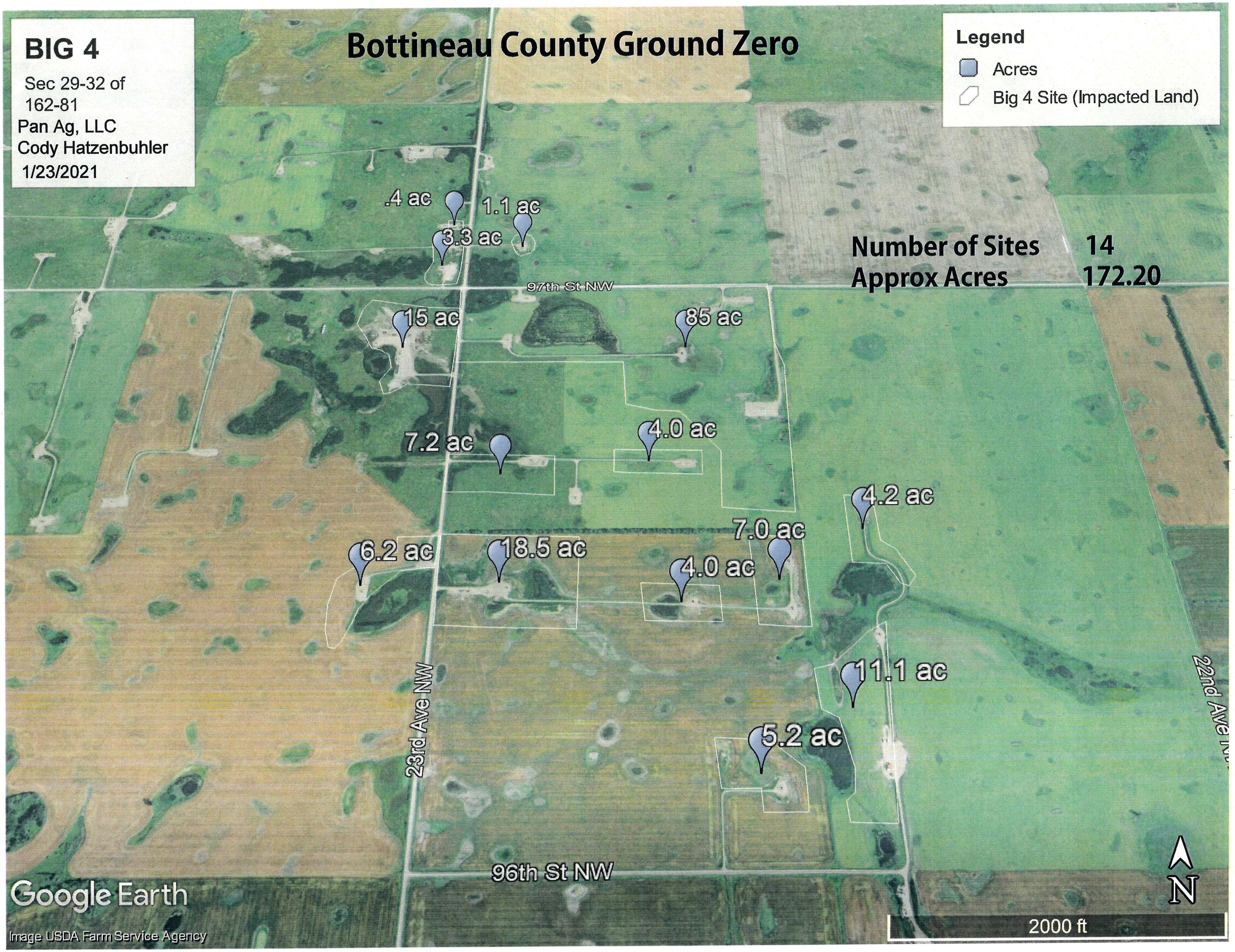


BIG 4
Sec 29-32 of
162-81
Pan Ag, LLC
Cody Hatzenbuhler
1/23/2021
Bottineau County Ground Zero
Legend
Acres
Big 4 Site (Impacted Land)
Number of Sites 14
Approx Acres 172.20
.4 ac
1.1 ac
3.3 ac
97th St NW
15 ac
85 ac
7.2 ac
4.0 ac
4.2 ac
7.0 ac
6.2 ac
18.5 ac
4.0 ac
11.1 ac
5.2 ac
23rd Ave NW
22nd Ave NW
96th St NW
Google Earth
Image USDA Farm Service Agency
N
2000 ft

2021 HOUSE STANDING COMMITTEE MINUTES

Energy and Natural Resources Committee
Coteau AB Room, State Capitol

HB 1401 PM
1/28/2021

Relating to monitoring and regulation of special waste in ground water and to provide a penalty

3:45 PM
Present: Representatives Porter, Damschen, Anderson, Bosch, Devlin, Heinert, Keiser, Lefor, Marschall, Roers Jones, Guggisburg, M Ruby, and Zubke. Absent: Rep Ista

Lynn Helms came at the request of the Chairman to answer questions.

Discussion Topics:
- Brine ponds
- Legacy wells
- 60's and 70's technology use
- Located sites
- Problem sites
- Owner responsibility sites
- Cost to eliminate sites
- State constitutional obligation to protect state

Closed the hearing at 4:08 PM.

Kathleen Davis, Committee Clerk

2021 HOUSE STANDING COMMITTEE MINUTES

Energy and Natural Resources Committee
Coteau AB Room, State Capitol

HB 1401
2/4/2021

Relating to monitoring and regulation of special waste in ground water and to provide a penalty

8:30 AM

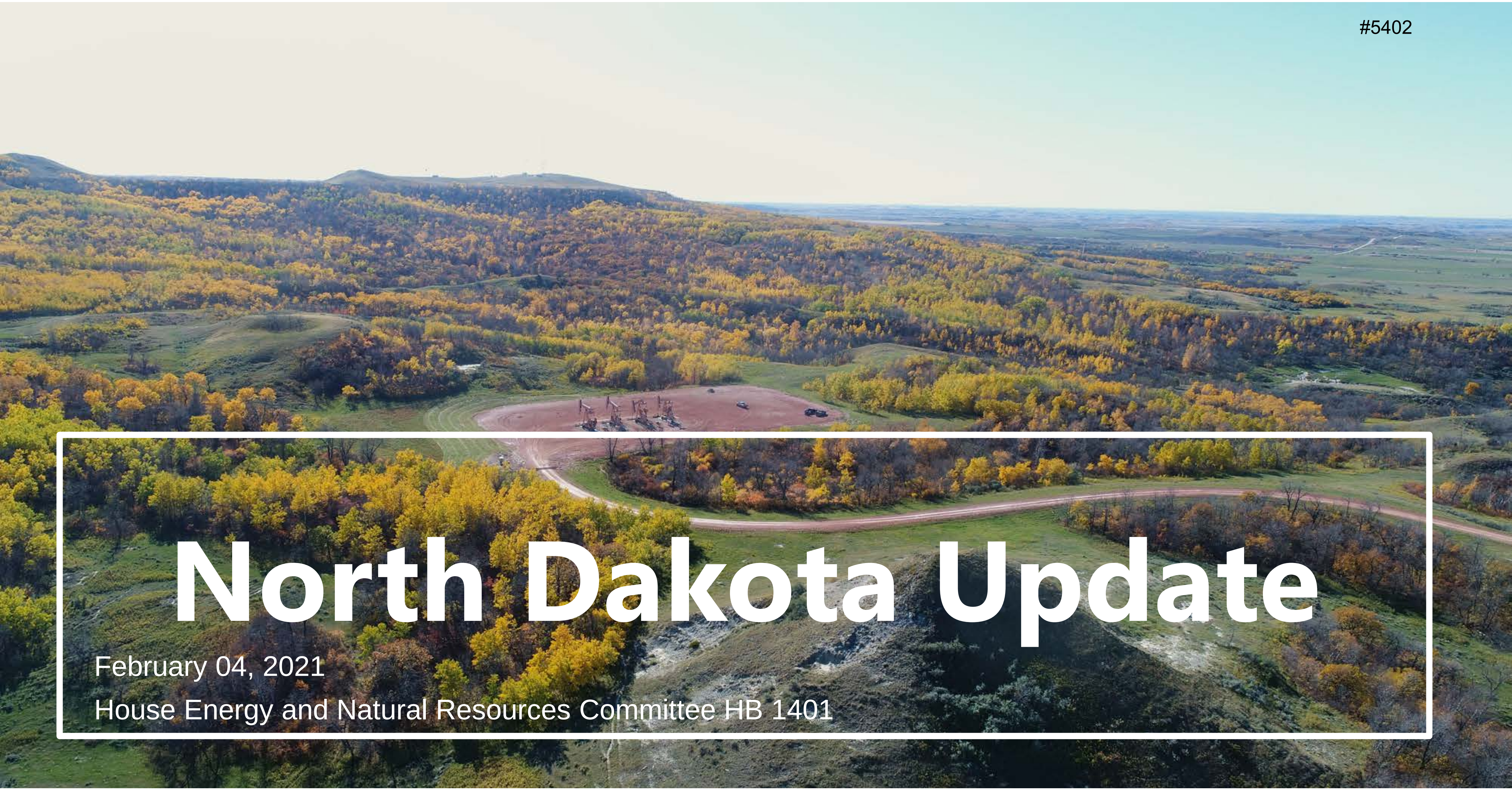
Vice Chair Damschen opened the hearing.
Present: Representatives Porter, Damschen, Anderson, Devlin, Heinert, Keiser, Marschall, Roers Jones, M Ruby, Zubke, Guggisberg, and Ista. Absent: Representatives Bosch and Lefor.

Discussion Topics:
- Problem legacy brine pits
- Background
- 2020 Update
- Budget

#5402 Lynn Helms, Oil and Gas Division

9:02 AM hearing closed.

Kathleen Davis, Committee Clerk



#5402

North Dakota Update

February 04, 2021

House Energy and Natural Resources Committee HB 1401

- Legacy Brine Pit Sites
- Background
- 2020 Update
- Budget

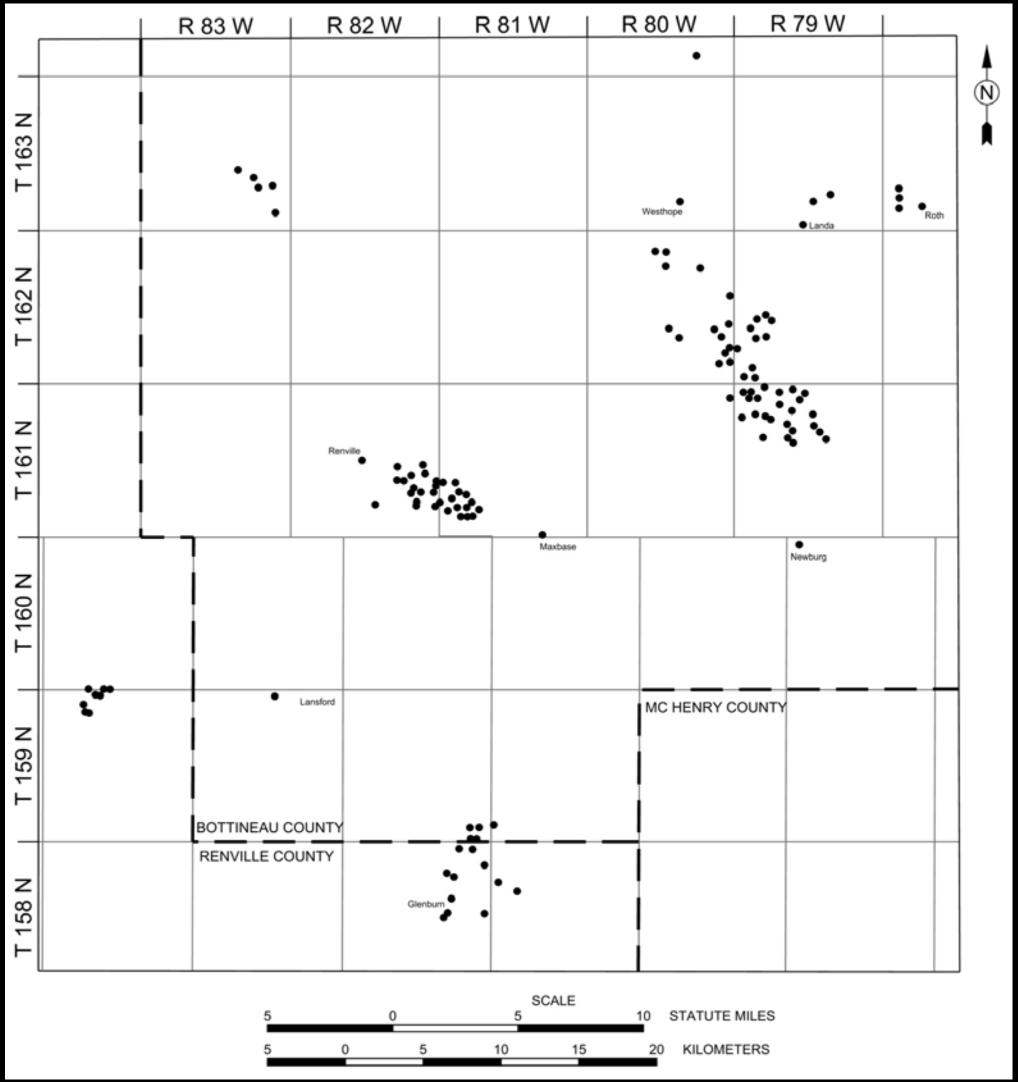
- Legacy Brine Pit Sites
- Background
- 2020 Update
- Budget

NDSU SOILS DEPT 1984 STUDY

Identified 121 old brine pond sites in Bottineau and Renville Counties.

Estimated the area contaminated by old brine ponds at 1,450 acres (average of 12 acres per site).

Interpreted aerial photographs from various years and scales.


R 83 W
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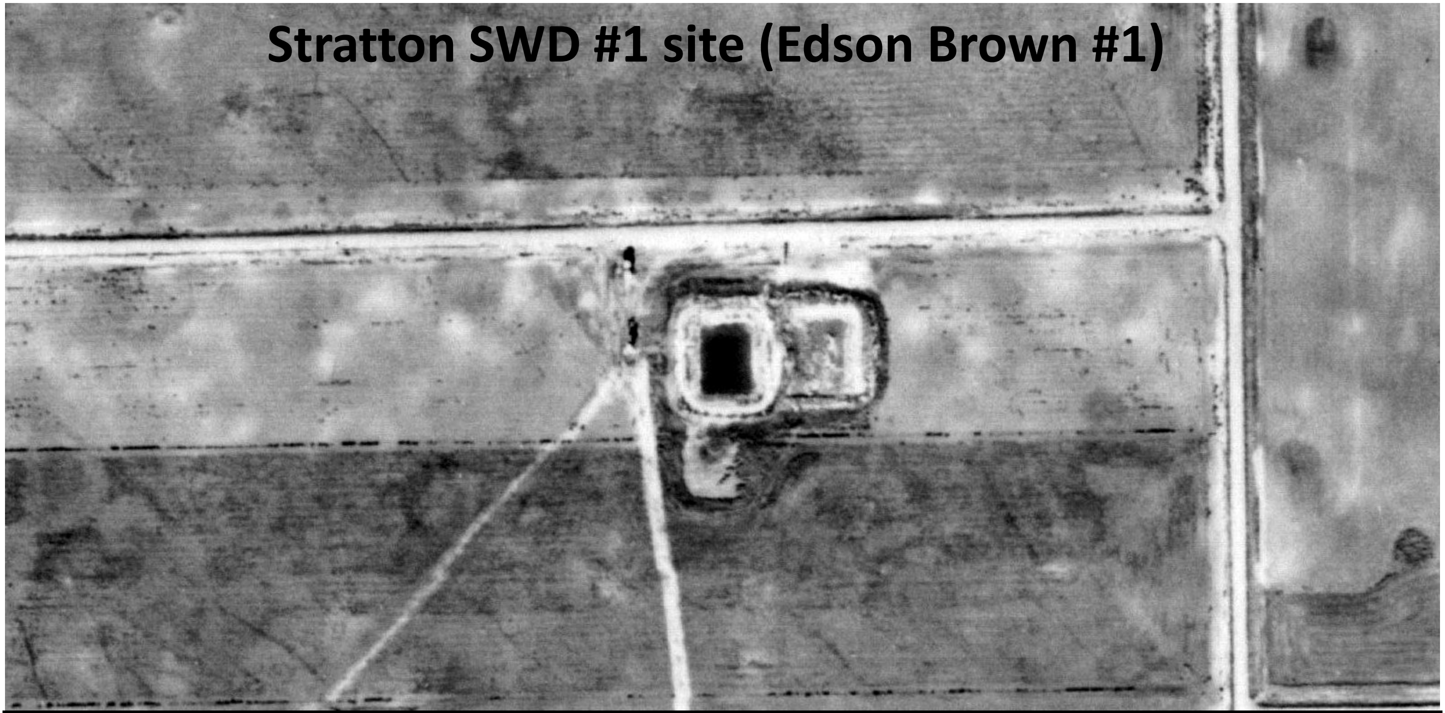
N
Westhope
Landa
Roth
Renville
Maxbase
Newburg
Lansford
MC HENRY COUNTY
BOTTINEAU COUNTY
RENVILLE COUNTY
Glenburn
SCALE
5 0 5 10 STATUTE MILES
5 0 5 10 15 20 KILOMETERS



1984

Drilled in 1959 by Cardinal Petroleum (Edson Brown #1).
Produced oil from 1959-1970.
Converted to a saltwater disposal well by Phillips Petroleum in 1978 (Stratton SWD #1).
The site contained two brine holding ponds from 1959 to at least 1970 (5 feet deep and 100 x 90 ft & 60 x 100 ft = 0.7 acres).
Produced 178,000 barrels of saltwater.

2005

A high salinity plume extends laterally around the site over an area of about 3 acres.
Plume restricted to till and not impacting any useable water supply (ND Health Dept. concurred in 2006).
High chloride levels at 160 feet (500 - 750 mg/l) appear to be coming from the underlying Fox Hills Formation (hydraulic heads).

Energy & Environmental Research Center

LEGACY BRINE PIT PROJECT

Wednesday, March 15, 2017

Presentation to the North Dakota Industrial Commission
Bismarck, North Dakota

Bethany Kurz
Principal Hydrogeologist

Critical Challenges. Practical Solutions.

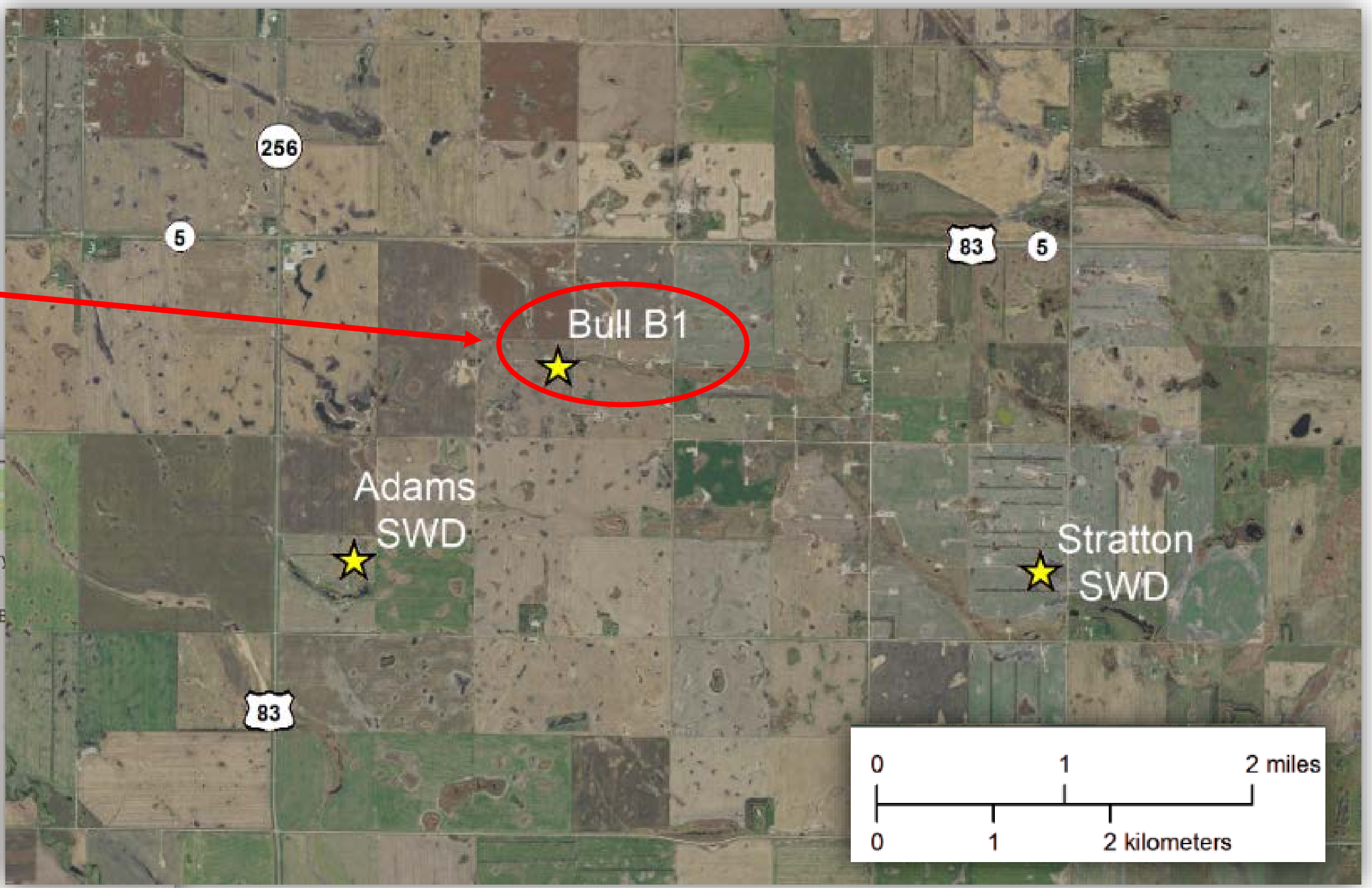
BACKGROUND

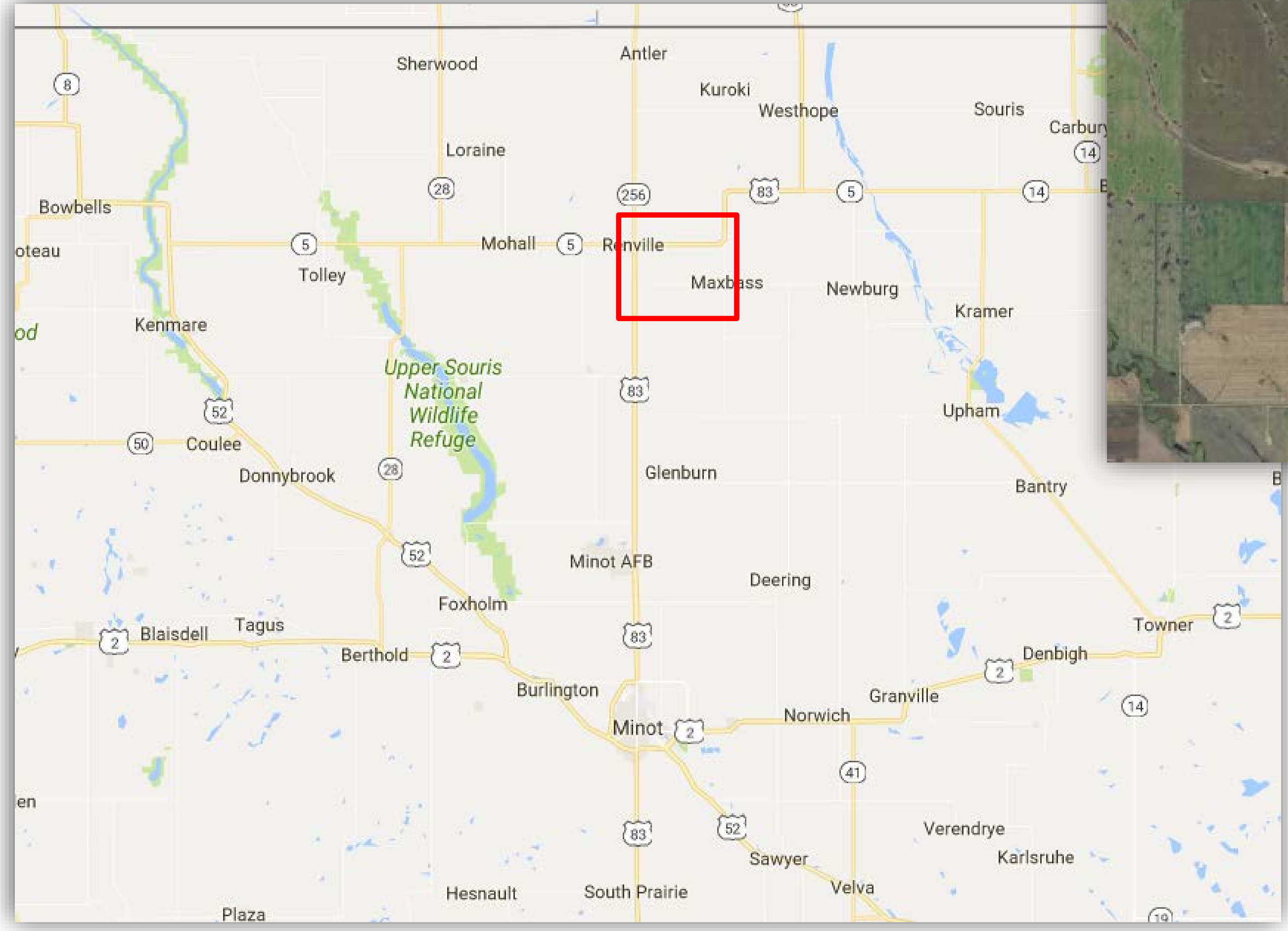
- Project goal
  - Apply a best practice, a common practice, and a novel remediation approach to a “representative” legacy brine pit site to assess the efficacy and cost of each.
- Project team
  - Energy & Environmental Research Center
  - Habitat Management, Inc.
  - Dakota Technologies, Inc.

EERC

SITE LOCATIONS

Initial Site Location





$450,000

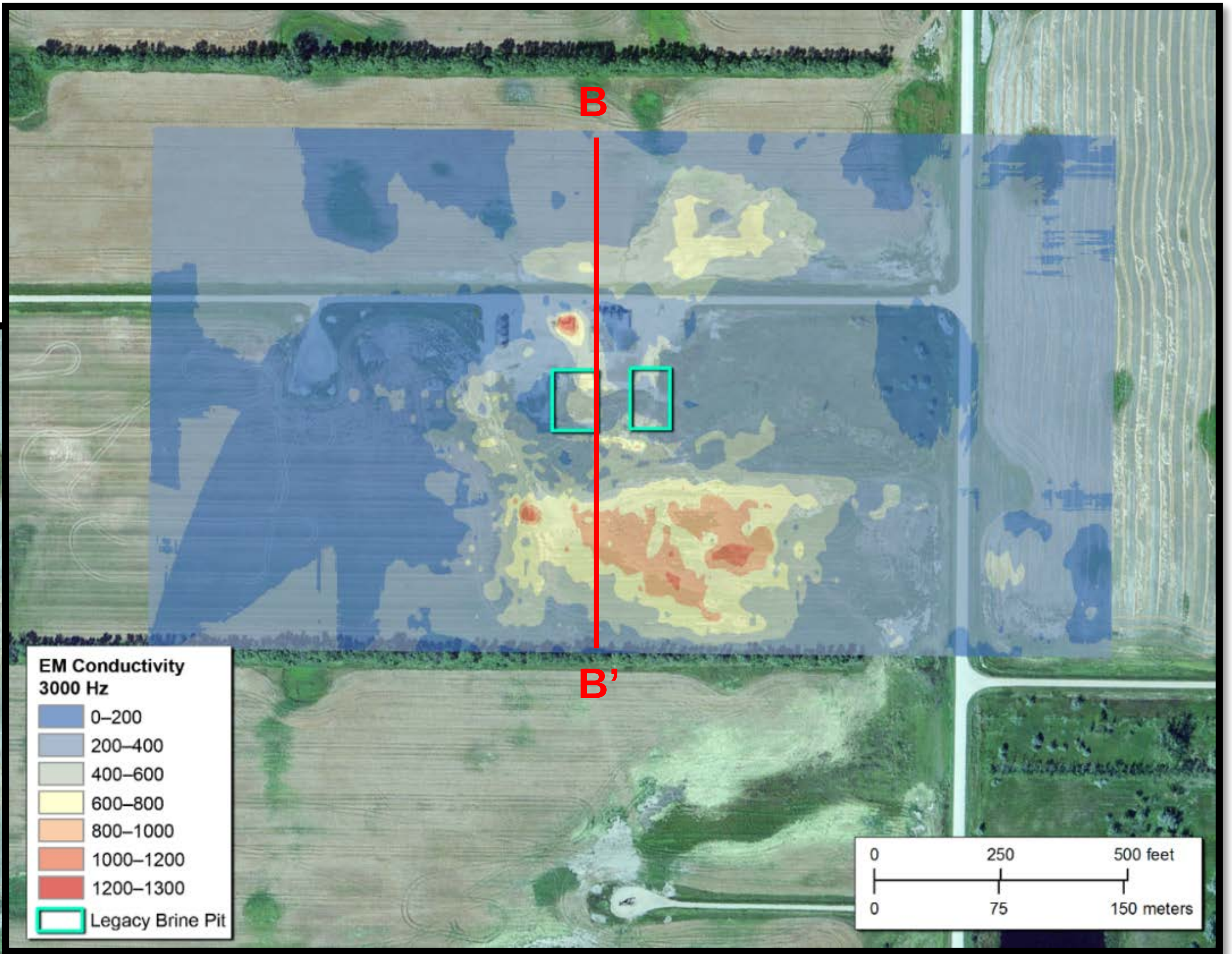
Critical Challenges. **Practical Solutions.**

ORIGINAL PROJECT OBJECTIVES

- Site characterization to determine areal and vertical extent of brine contamination
- Site remediation system design (drain tile, sumps, wells, irrigation, deep hydraulic delivery)
- Site preparation
- Extensive site irrigation at the best practice site area
- Hydraulic delivery of amendments at the novel technique site area
- Periodic, regular soil sampling until threshold levels are met

SITE #2: STRATTON SWD

NDIC File No. 2318
48.739°N 101.216°W
Spud Date: 05/07/1959

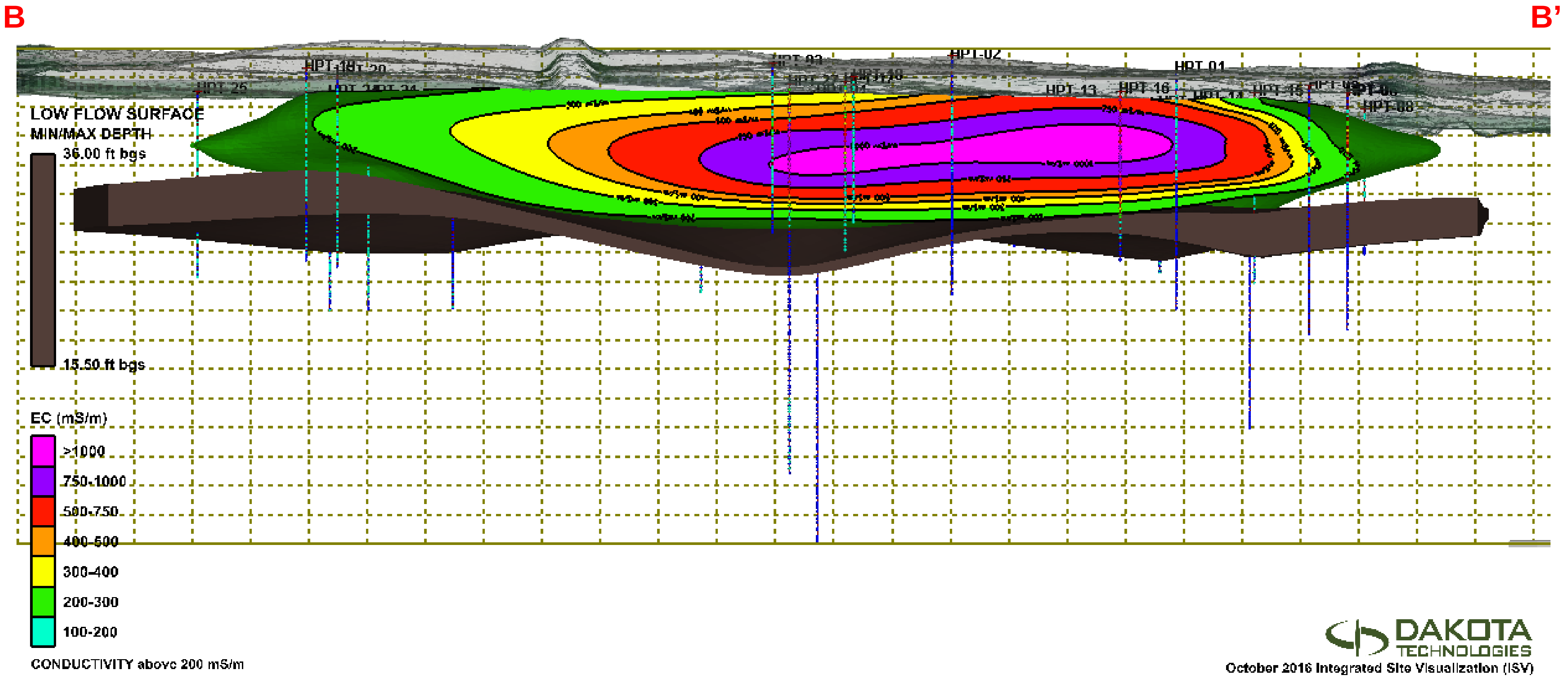


3D Visualization of Electrical Conductivity (mS/m)
EERC - 0265.16 (Stratton)
Minot, ND
Vertical Exaggeration = 5:1

CONDUCTIVITY above 200 mS/m

Vertical Slice, Easting = 1,795,843.0 ft

Stratton SWD Site



DAKOTA TECHNOLOGIES
October 2016 Integrated Site Visualization (ISV)

KEY CONCLUSIONS

- Salt-impacted zones extend well beyond the original pit area and may be increasing in size.
  - Contaminant migration is exacerbated by the shallow water table in the Prairie Pothole Region.
- Soil remediation (soil amendments/irrigation) coupled with drain tile may be a mechanism to remediate the near-surface soils (0–6 feet), but costs are highly dependent on availability of freshwater supplies for irrigation as well as disposal options for the drain tile effluent.
- Given the low-permeability of the soils, in situ treatment of the deeper zones will likely be challenging, and excavation of the contaminated soils is very expensive.

Reclamation Options for Legacy Brine Waste Pits in North-central North Dakota: Effects of remediation techniques on grass species

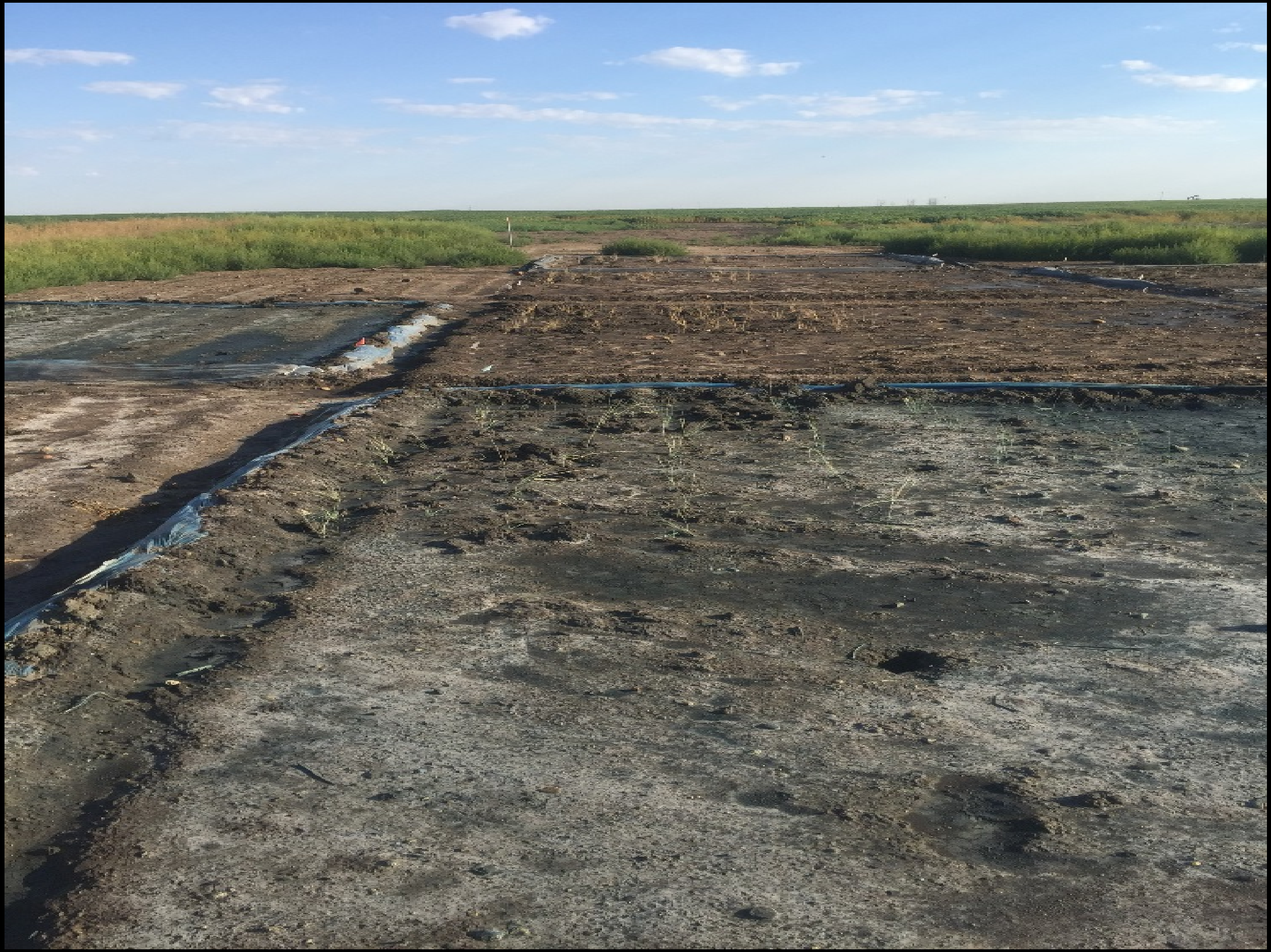
Funded by Abandoned Oil and Gas Well Reclamation Fund 405-448-15

Drs. Ryan Limb, Kevin Sedivec, Aaron Daigh, and Tom DeSutter

School of Natural Resource Sciences

North Dakota State University

NDSU Field Studies – 2016



Survivability of Grass Plugs and Seedlings on Legacy Brine Spills using Amendments

Amendments

- Compost
- Gypsum
- Combination of Compost and Gypsum
- Ferric hexacyanoferrate ($C_{18}F_7N_{18}$) crystallization inhibitor
- Control

Plugs and Seed Survival

- Plugs planted in August
- Seeds planted in October (dormant seeding)
  - *Western wheatgrass*
  - *Inland saltgrass*
  - *Alkali sacaton*

North of Glenburn, ND in Bottineau County(T157N, R82W, NW1/4 Section 36)

Leaching Column Results

- No difference between amendment types (commercial vs gypsum)
- There was a more than one magnitude reduction in EC (78.4 to 4.67 dS m^{-1}) for all treatments after trial termination.
  - Based on these findings, we CAN MOVE water and salt down the soil profile

Findings to Date
$435,759

- Ferric hexacyanoferrate ($C_{18}F_7N_{18}$) crystallization inhibitor DID NOT work on legacy sites
- Nuttall alkaligrass, alkali sacaton, inland saltgrass were superior grass species to plant on brine impacted soils
  - Western wheatgrass worked successfully on soils with EC levels < 20 dS m^{-1}

GOLDER

NDIC Brine Pond Study

Phase II: Site Assessments

Submitted to:

North Dakota Department of Mineral Resources - Oil and Gas Division

1016 E Calgary Ave

Bismarck, ND 58503

Submitted by:

Golder

2000 Schafer Street, Suite H, Bismarck, North Dakota 58501, USA

+1 701 258 5905

June 25, 2018

rev. September 10, 2018

$83,159

North Central Area

216 potential sites

166 sites in aerial photos (Golder)

52 no visual impacts (Golder)

114 impacted sites (Golder)

9 settlements identified (Barr)

105 potential remediation sites

100 square feet - 5.75 acres

BARR

Brine Pond Landowner Compensation Research Summary Report

Bottineau, Renville and Ward Counties

Prepared for

North Dakota Industrial Commission

August 31, 2018

Barr Engineering Co. 234 W. Century Ave. Bismarck, ND

$35,698

Brine Pond Remediation Techniques

Project No. 405.2-17-010

$429,120

Terracon

Drone Aerial Photography

2017

Site B21-13 **South of Site Looking North Prior to Field Work**

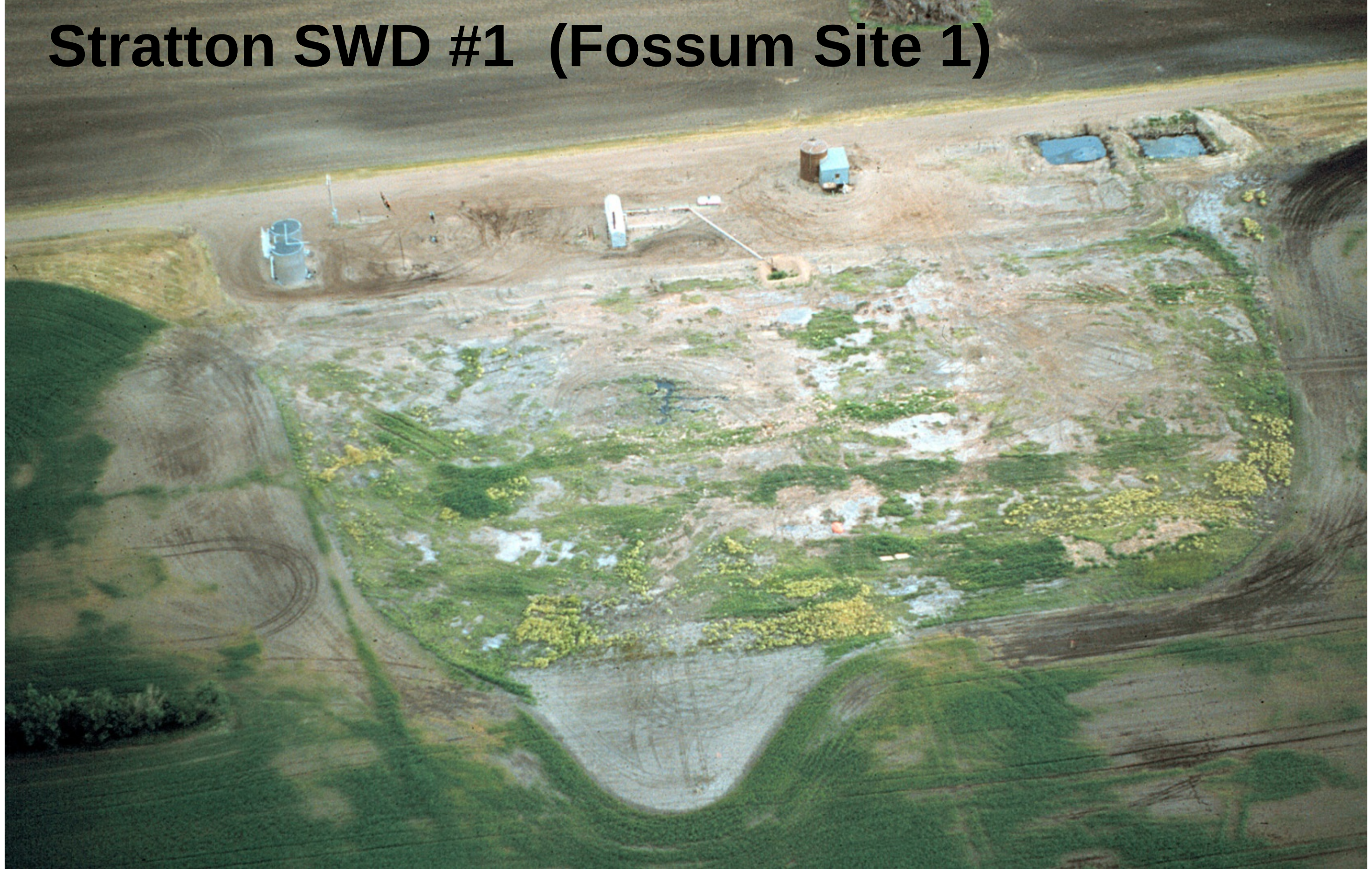
A high salinity plume extends laterally around the site over an area of 250,000 ft2 (about 6 acres).

Plume extends to a depth of over 80 feet (highest concentrations in top 40 feet).

Plume restricted to till and not impacting any useable water supply (ND Health Dept. concurred in 2006).

High chloride levels at 160 feet (500 - 750 mg/l) appear to be coming from the underlying Fox Hills Formation (hydraulic heads).

Stratton SWD #1 (Fossum Site 1)



1985

A high salinity plume extends laterally around the site over an area of 250,000 ft2 (about 6 acres).

Plume extends to a depth of over 80 feet (highest concentrations in top 40 feet).

Plume restricted to till and not impacting any useable water supply (ND Health Dept. concurred in 2006).

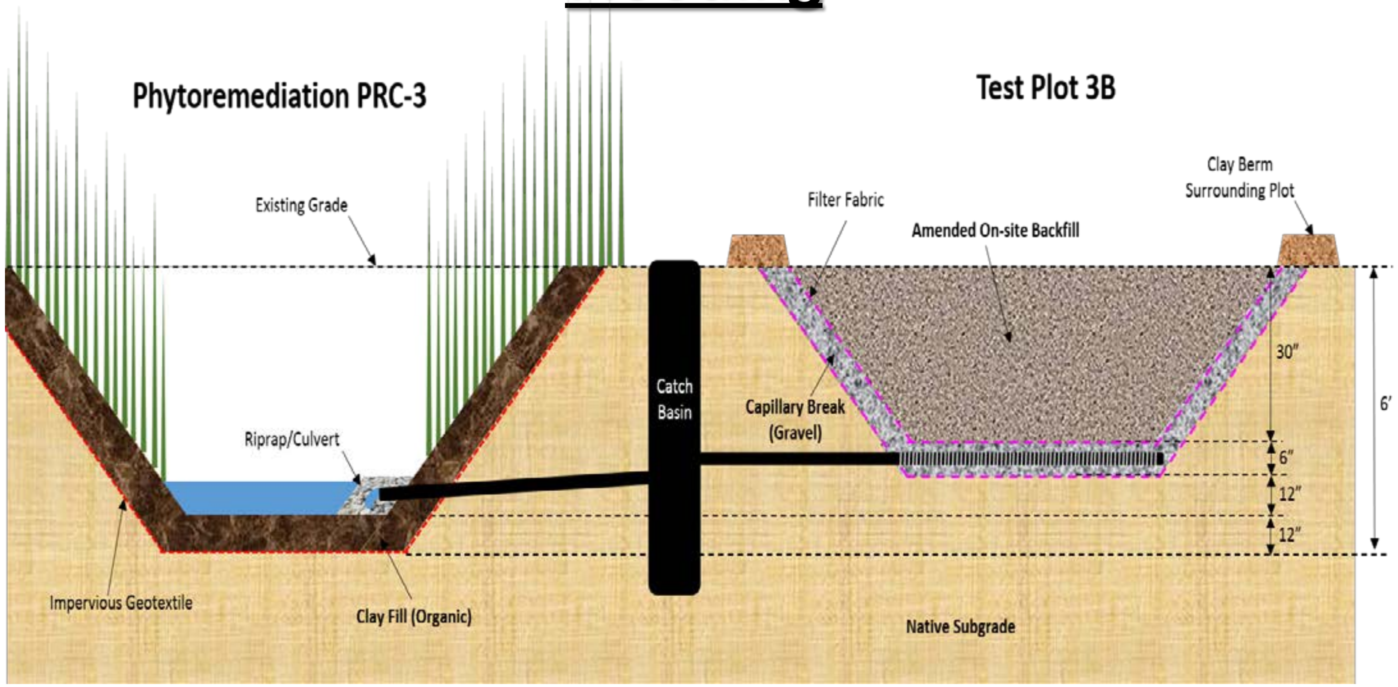
High chloride levels at 160 feet (500 - 750 mg/l) appear to be coming from the underlying Fox Hills Formation (hydraulic heads).

Tested 9 different techniques 2017-2018

$655,396

3B performed best

Test Plot 3B – Amended Soil with Water Flooding



3B Diagram
Test 3B on a typical 1-2 acre site in 2020

- Legacy Brine Pit Sites
- Background
- 2020 Update
- Budget

2019

Photo #1 View of remediation area prior to commencing work.

2019

Photo #2 Initial earthwork and removal of topsoil.

2019

Photo #3 Stockpiling topsoil and excavated contaminated soil.

2019

Photo #4 Soil Excavation.

2019

Photo #5 Excavation of phytoremediation cell.

2019

Photo #6 Installation of capillary break.

2019

Photo #7 Installation of PVC drain tile in the capillary break with filter fabric.

2019

Photo #8 Placing gypsum and straw amended soil over capillary break.

2019

Photo #9 Remediation area with hoses and sprinklers laid out.

$342,602

2020

Photo #11 Wheat growth in the remediation cell compared to the surrounding wheat fields.

The phytoremediation approach to remediating this site required less time, equipment, soil disposal and soil delivery ultimately leading to significantly reduced costs for remedial actions. As presented in the Limited Site Investigation (LSI) with Corrective Action Plan (CAP) dated September 3, 2019 and this report, based on the progression of field and analytical data collected between August 2019 and July 2020, this technique appears to meet the hypothesis and goal of this brine remediation study.

It was observed that limited areas along the developed berm of the remediation zone have spots that are currently bare ground and not maintaining the desired vegetation growth. This is believed to be due to the steep outer perimeter slope to the east north, east and south being constructed of the same amended soil, yet not receiving the flooding procedure that the central area did. It should be noted that there may be a thinner crop growth this year due to the volume of water stripping the soil of nutrients. Terracon recommends utilizing a bioremediation fluid surface treatment in these areas to assist in the revegetation process. Additionally, Terracon recommends continued monitoring for the 2021 crop season with spray applications as needed based on field observations.

- Legacy Brine Pit Sites
- Background
- 2020 Update
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Budget with Brine Pond Remediation

Fiscal Year	Wells	Well Plug & Reclaim	Illegal Dumping	Legacy Sites	Brine Ponds	Total	Fund Balance		
2007	4,603	$231,911				$7,500,000	Revenue/year		
2008	5,483	$26,750							
2009	5,547	$141,089							
2010	6,409	$0							
2011	7,746	$142,729							
2012	9,760	$87,026							
2013	11,945	$0	$283,389						
2014	14,377	$0	$1,387,223						
2015	15,853	$49,749	$127,058	$102,201		$279,008	$11,500,000		
2016	16,513	$1,800,000	$19,407	$1,200,000	$450,000	$3,469,407	$14,030,593		
2017	17,527	$82,075	$6,665	$340,716	$435,759	$865,215	$15,190,378		
2018	18,749	$87,794	$187,577	$1,694,700	$429,120	$2,399,191	$14,791,187		
2019	19,999	$93,648	$124,819	$1,694,700	$118,857	$2,032,024	$22,139,680	0	
2020	20,380	$73,502	$124,819	$1,335,413	$261,501	$4,256,530	$25,654,211	1	$1,695,237
2021	21,276	$10,000,000	$124,819	$1,000,000	$81,101	$13,944,626	$16,517,736	0	
2022	22,172	$2,500,000	$124,819	$500,000	$1,000,000	$4,124,819	$19,892,917	13	
2023	23,068	$3,500,000	$124,819	$500,000	$1,000,000	$5,124,819	$22,268,098	13	
2024	24,348	$3,500,000	$124,819	$500,000	$1,000,000	$5,124,819	$24,643,278	13	
2025	25,628	$1,000,000	$124,819	$1,694,700	$2,305,300	$5,124,819	$27,018,459	31	
2026	26,908	$750,000	$124,819	$1,694,700	$2,555,300	$5,124,819	$29,393,640	34	$7,941,701
	Total	$24,066,274	$3,009,874	$12,257,130	$9,636,938	$59,370,098	$243,040,177	105	

North Dakota Law Review

Volume 54 | Number 4 Article 2

1977

The Public Trust Doctrine in North Dakota

Don Negaard

2. *Resources Attached With the Public Trust*

Historically, the public trust has attached to such resources as tidelands, lands beneath lakes, land beneath a state's navigable waters, water in whatever form, and parklands.

Purposes protected by the Public Trust Doctrine include navigation, fishing, and hunting.

North Dakota has developed a trust concept in relation to an easement held for the public in the congressional section lines of the state for transportation purposes. North Dakota is not alone in applying the trust to these easements.

Water appears to be the resource most affected by Public Trust Doctrine.

> The idea of the navigable stream beds being held in trust is consonant with the public's right to travel upon the waters. Riparian landowners and appropriators do not own the streams from which they receive their water but merely have a usufructuary right.
>
> 61-01-01. Waters of the state - Public waters. All waters within the limits of the state from the following sources of water supply belong to the public and are subject to appropriation for beneficial use and the right to the use of these waters for such use must be acquired pursuant to chapter 61-04:
> 1. Waters on the surface of the earth, excluding diffused surface waters but including surface waters whether flowing in well-defined channels or flowing through lakes, ponds, or marshes which constitute integral parts of a stream system, or waters in lakes;
> 2. Waters under the surface of the earth whether such waters flow in defined subterranean channels or are diffused percolating underground water;
> 3. All residual waters resulting from beneficial use, and all waters artificially drained; and
> 4. All waters, excluding privately owned waters, in areas determined by the state engineer to be noncontributing drainage areas. A noncontributing drainage area is any area that does not contribute natural flowing surface water to a natural stream or watercourse at an average frequency more often than once in three years over the latest thirty-year period.

IV. CONCLUSION

The common law Public Trust Doctrine is not and should not be a substitute for careful planning by legislative and administrative officials charged with co'ordinating allocation and disposition of the publicly owned resources of North Dakota. Beneficial industrial development planning requires a much higher degree of social responsibility than is presently required by the minimal safeguards provided by the Public Trust Doctrine.

What the Public Trust Doctrine does provide for the citizens of North Dakota is a judicially developed safeguard with procedural and substantive limitations applied to dispositions of resources which are allocated by the public to the private sector. The Public Trust Doctrine accomplishes this by providing standing in the courts for concerned citizens who wish to challenge an allocation of resources that they feel is not in the public interest. The Public Trust Doctrine serves the interests of the public when a governmental body which is required to represent the public ignores or reacts arbitrarily with regard to the terms of the trusteeship with which the public has been vested with property rights. As a short term concept it can and will provide a minimum standard for review of governmental action but is no substitute for careful, detailed planning and mandatory legislative guidelines for wise energy related development.

North Dakota Department of Mineral Resources

www.dmr.nd.gov

Phone: 701.328.8020 Email: oilandgasinfo@nd.gov

Mailing Address: 600 East Boulevard Ave. Dept 405; Bismarck, ND 58505

2021 HOUSE STANDING COMMITTEE MINUTES

Energy and Natural Resources Committee
Coteau AB Room, State Capitol

HB 1401
2/5/2021

Relating to monitoring and regulation of special waste in ground water and to provide a penalty

9:00 AM

Present: Representatives Porter, Damschen, Anderson, Bosch, Devlin, Heinert, Keiser, Marschall, Roers Jones, M Ruby, Zubke, and Ista. Absent: Representatives Lefor and Guggisberg

Rep D. Anderson moved a Do Not Pass, seconded by Rep Roers Jones.

Representatives	Vote
Representative Todd Porter	Y
Representative Chuck Damschen	Y
Representative Dick Anderson	Y
Representative Glenn Bosch	Y
Representative Bill Devlin	Y
Representative Ron Guggisberg	AB
Representative Pat D. Heinert	Y
Representative Zachary Ista	N
Representative George Keiser	Y
Representative Mike Lefor	AB
Representative Andrew Marschall	Y
Representative Shannon Roers Jones	Y
Representative Matthew Ruby	Y
Representative Denton Zubke	Y

Motion carried. 11 – 1 - 2 Rep D Anderson is carrier.

9:05 am

Kathleen Davis, Committee Clerk

REPORT OF STANDING COMMITTEE

HB 1401: Energy and Natural Resources Committee (Rep. Porter, Chairman) recommends **DO NOT PASS** (11 YEAS, 1 NAY, 2 ABSENT AND NOT VOTING). HB 1401 was placed on the Eleventh order on the calendar.